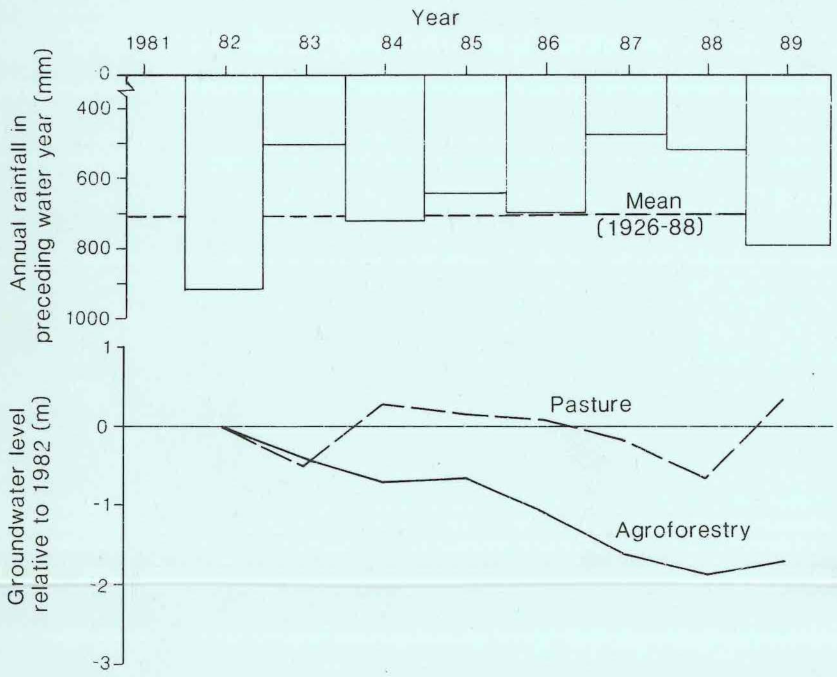
Groundwater Level and Salinity response under Agroforestry at Stene's Farm in the Darling Range of Western Australia

by M.A.Bari, N.J.Schofield and D.W.Boyd



Report No. WS 77

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Water Authority of Western Australia

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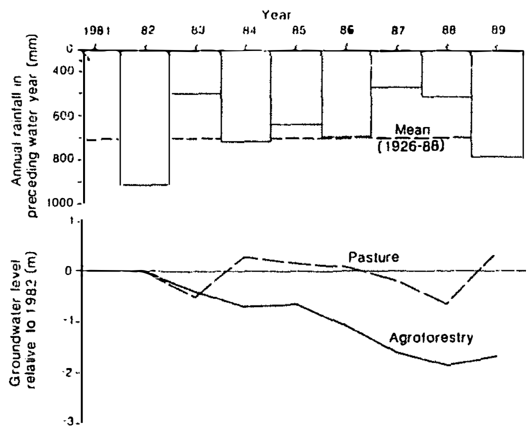

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SUMMARY

Stream and groundwater salinities have increased in the south-west of Western Australia due to the replacement of deep-rooted, native, perennial vegetation with shallow-rooted annual agricultural crops and pastures. The clearing of native vegetation has resulted in a decrease in evapotranspiration and an increase in groundwater levels. The rising groundwater mobilises salt previously 'stored' in the unsaturated zone and discharges it to the land surface and the streams. Research into lowering groundwater levels by increasing evapotranspiration through partial reforestation of the cleared land began in the 1970s.

One important partial reforestation strategy involves planting trees in wide-spaced rows or grids allowing agriculture to grow between the trees. This option, known as agroforestry, has been hydrologically studied at three sites in Western Australia. This report describes the groundwater level and salinity response to an agroforestry plantation at Stene's Farm (~700 mm yr^{-1} rainfall) in the Darling Range of Western Australia. Groundwater level and salinity data have been analysed for the period 1982 to 1989.

During the study period (1982-89), the minimum groundwater level under agroforestry declined 2.0 m relative to a pasture control site. The rate of reduction was fairly uniform which is probably attributable to the continuous crown growth of the plantations. The maximum water level reduction was 1.1 m relative to the control site.

The annual changes in minimum groundwater level were compared with the rainfall of the preceding year. The results indicated if annual rainfall was less than 610 mm over the pasture site, the minimum groundwater level would decline in the following year. Similarly, the minimum groundwater level beneath agroforestry would decrease if the preceding year's rainfall was below 775 mm. Over the period 1982-89 annual rainfall was 13% lower than the long term average. The results indicated the

minimum groundwater level would have risen under pasture and would have fallen under agroforestry if long term average rainfall conditions had occurred.

Groundwater salinity under agroforestry reduced by 5% during the study period. Under pasture the reduction in groundwater salinity was much greater (40%).

The declining water table and decreasing groundwater salinity should reduce stream salinity. Stene's Farm lies within the Collie River Catchment. It is proposed to review stream salinity data at Stenes Farm as part of a report on stream salinity in the Collie River Catchment.

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1. INTRODUCTION

Stream salinisation is a major and increasing problem in southern Western Australia (Schofield et al., 1988; Schofield and Ruprecht, 1989). One of the most promising options to control and reverse salinisation is partial reforestation (Schofield et al., 1989). Various reforestation strategies embracing different combinations of trees and agriculture have been tested in Western Australia (W.A.). One such strategy is agroforestry which involves planting trees at a wide spacing over a high proportion of the agricultural land.

Agroforestry has been researched for some 12 years in W.A. It has been demonstrated that agroforestry can increase total land productivity above that of agriculture or forestry alone (Malajczuk et al., 1984; Anderson and Moore, 1987; Anderson et al., 1988). There are also potential environmental benefits from the use of agroforestry, including shelter for animals, erosion control and salinity control (Batini et al., 1983).

An agroforestry research site was established at Stene's Farm in Wellington Dam catchment in 1978. The site consists of eucalypts thinned to five different stem densities. One principal objective of the study was to determine the extent to which the plantations could lower the groundwater table, which in turn should reduce groundwater solute discharge to streams. This report represents the most in depth and up-to-date analysis of data from this site and is an important contribution to the assessment of agroforestry as a salinity control strategy. Earlier, less detailed hydrological analyses of data from this site have been reported by Anderson et al. (1982), Edgeloe et al. (1984), Bell et al. (1988) and Schofield et al. (1989). The results are compared to a similar agroforestry study carried out at Flynn's Farm in the Mundaring Weir catchment (Bari et al., 1990).

2. SITE DESCRIPTION

2.1 Location

The experimental site is located in the Darling Range, approximately 40 km North of Collie (Fig. 1). It lies within the predominantly forested Wellington Dam catchment.

2.2 Site History and Layout

The experimental site consists of two parts : the agroforestry site and control site (Fig. 1). Both sites comprise part farmland (pasture), native forest and reforestation. Clearing of the native forest for pasture development took place during the 1950s. In 1976 the site was purchased by the State Government as part of a programme to reforest farmland within Wellington Dam catchment to control the inflow salinity to Wellington Reservoir.

The agroforestry site has a catchment area of 120.5 ha and is more or less rectangular in shape (Fig. 2). The Bingham River flows through the middle of the catchment. During the study period the annual flow-weighted average salinity of Bingham River varied from 258 mg L^{-1} to 1496 mg L^{-1} TSS. By 1976 about 25% of the catchment was cleared. Clearing took place on the lower slopes of the agroforestry site. The plantation was established in 1978 covering 14% of the catchment and roughly equally distributed on the two sides of the river. A 200 m by 400 m strip was left cleared for sheep grazing south of the plantation blocks.

The control site lies to the east of the agroforestry catchment (Fig. 1). About 31% of the total area had been cleared leaving very little native vegetation near the river on the valley floor. Between 1976 and 1978, strip reforestation was carried out on the lower slopes covering about 14% of the cleared area. The groundwater control bores are situated in the middle slopes, between the reforestation and the native forest.

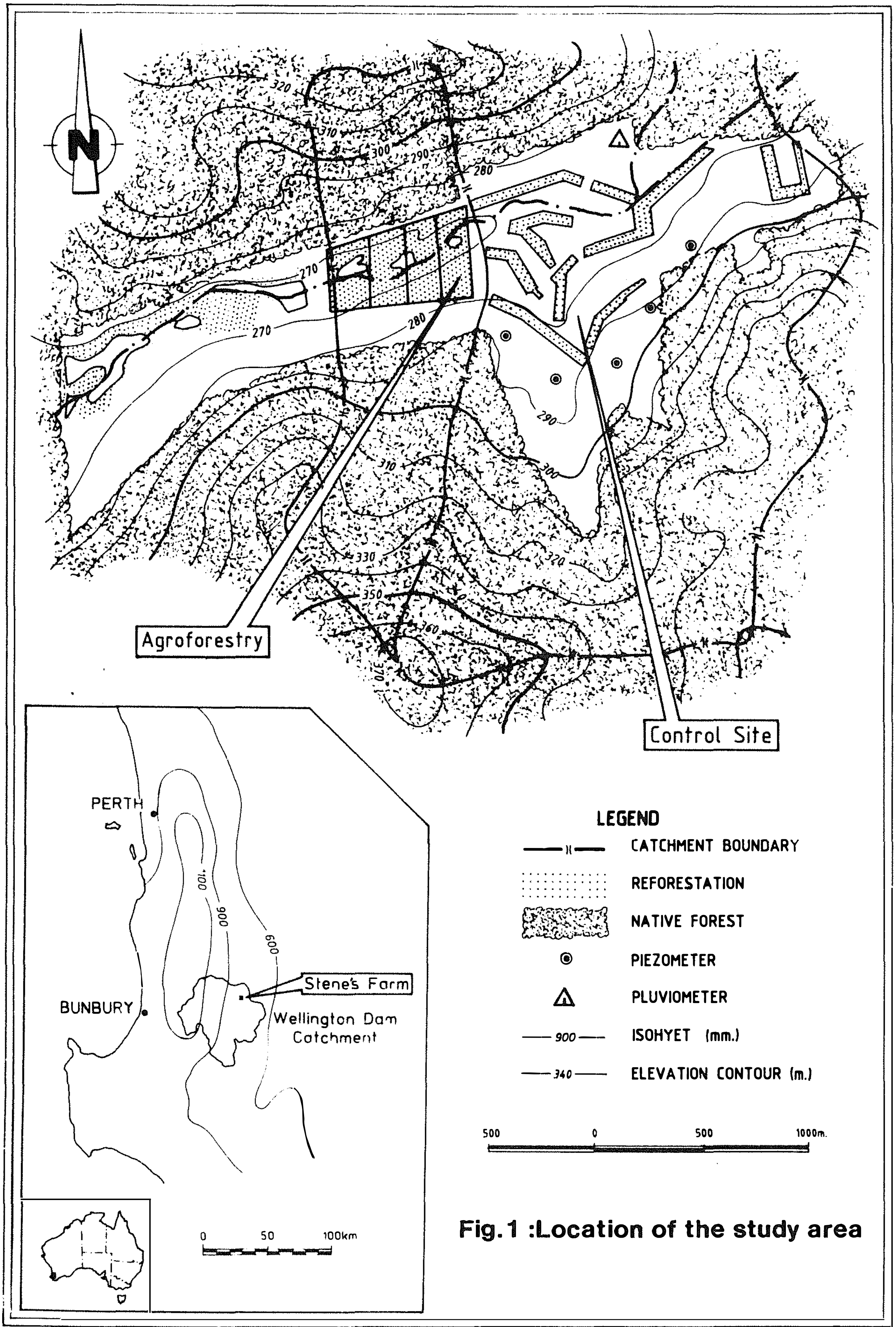


Fig.1 :Location of the study area

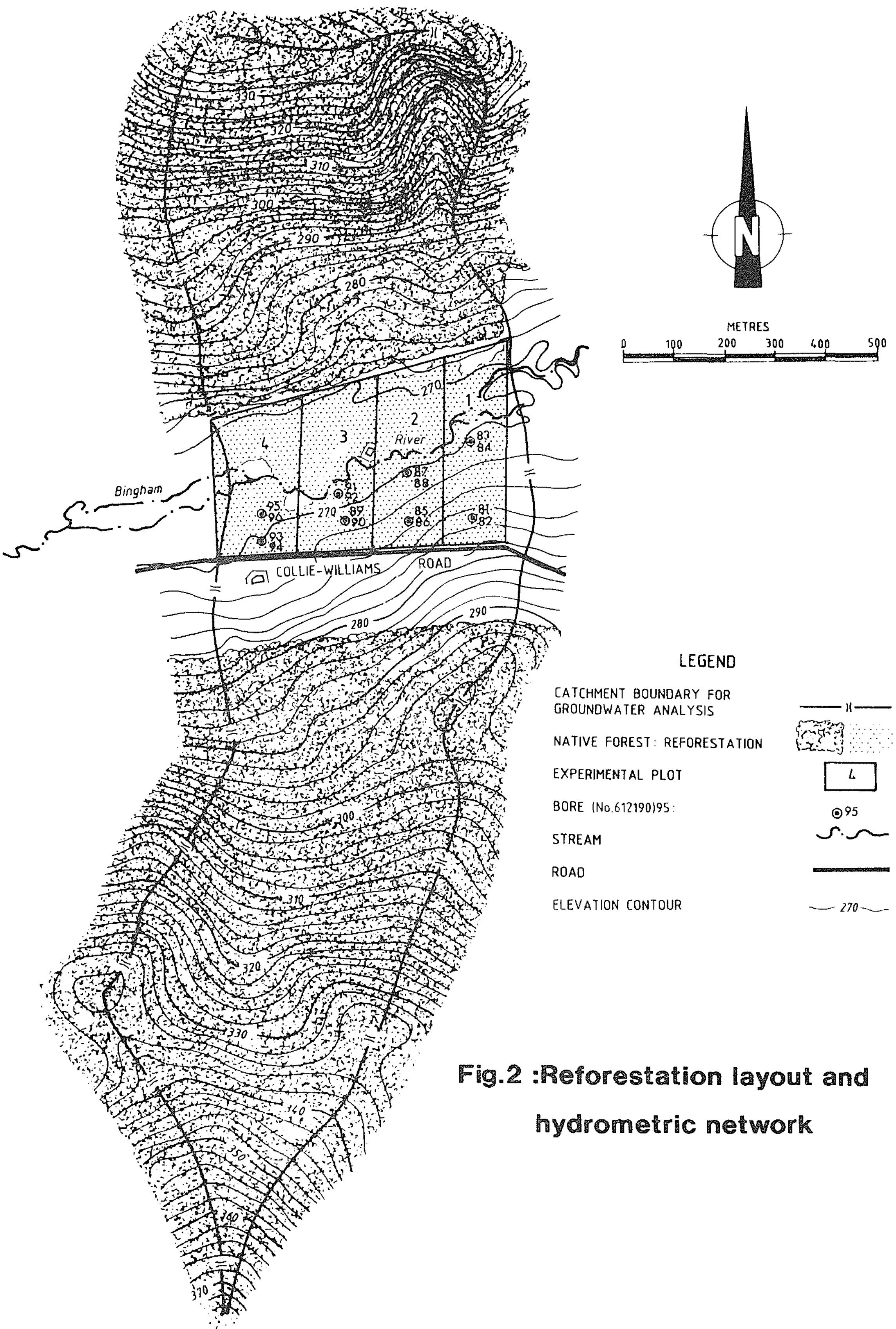


Fig.2 :Reforestation layout and hydrometric network

2.3 Climate

The Wellington catchment area has a Mediterranean climate with cool, humid, wet winters and hot, dry summers. About 80% of the total annual rainfall occurs in winter. The long term average rainfall (1926 to 1988) of the experimental site is estimated to be 713 mm yr^{-1}. The annual average pan evaporation of the catchment is 1600 mm (Luke et al., 1988). Temperatures range from a maximum in excess of 40°C, which could be expected to occur in January to February, to a minimum of less than 0°C occurring in June or July.

2.4 Topography

The topography of the agroforestry catchment is shown in Fig. 2. The experimental bores are located in the reforested portion where ground slope averages 4.3%.

The elevation of the control site varies from 271 m AHD to 374 m AHD. The mean slope of the site is 3.8%, which is comparable to the agroforestry catchment.

2.5 Soil and Geology

The surface soils of both sites are highly permeable and the rainfall intensity rarely exceeds the infiltration capacity of the soil. Soil profiles are generally lateritic and of granitic origin. The profile mainly consists of shallow sands and clayey gravels of variable thickness overlying a sandy clay subsoil. The depth of weathering is probably more than 20 m.

The soil and geology of the control site have a close similarity to that of the agroforestry site. Sand and sandy clays are common near the surface, while the subsoil has a variable sandy clay matrix. The depth of weathering of this site is also more than 20 m.

2.6 Vegetation

Prior to reforestation the cleared area of the agroforestry site had a germination of annual rye, barley and other grasses, and it had been intensively grazed. Five species of Eucalyptus were planted in 1978 (Table 1), details of which are given in Section 4. The upslope native vegetation is dominated by jarrah (E. marginata) with the principal sub-dominants being marri (E. calophylla) and wandoo (E. wandoo).

On the lower slope of the control site there is reforestation covering about 14% of the cleared area, comprising two species of pinus and eleven species of Eucalyptus planted in strips during the period 1976-78. The remainder of the site was left under pasture (Fig. 1).

Table 1 : Hydrogeological and Plantation Details of Stene's Agroforestry Site

Block No.	Hydrogeological			Reforestation								
	Area (ha)	SWRIS Bore No.	Initial Depth to Water table (m)	Species Planted	% area of block planted	Stem Density (Stems ha^{-1})			Thinning Period (Stem ha^{-1})		Present Density (Stems ha^{-1})	Crown Cover (%)
						1978	1981	1982	1981	1982		
A	4.5	61218082	3.90	E. Sargentii	16	1250	660	600	May	Feb	568	31
		61618084	2.20	E. Wandoo	10							
				E. Camaldulensis	63							
				E. Calophylla	11							
B	4.5	61618086	5.08	E. Sargentii	22	1250	660	300	May	Feb	309	22
		61618088	1.98	E. Wandoo	10							
				E. Camaldulensis	68							
C	4.5	61618090	1.19	E. Sargentii	42	1250	-	900		Feb	627	28
		61618092	1.65	E. Camaldulensis	39							
				E. Wandoo	19							
D	4.5	61618094	2.72	E. Sargentii	31	1250	660	150	May	Feb	163	20
		61618096	2.74	E. Camaldulensis	69							

3. EXPERIMENTAL OBJECTIVES

3.1 Plantation

The main objective of the agroforestry trial was to test the effect of different stem densities on groundwater levels. To meet the objective, four plantations were established side by side at right angles to the streamline.

The block treatments were selected at random. Five species of *Eucalyptus* were planted in 1978 as shown in Fig. 2. The initial stem density across the whole site was 1250 per hectare.

3.2 Hydrology

The objectives of the groundwater monitoring programme were to:

(i) identify the initial groundwater conditions prior to agroforestry treatment;

(ii) determine seasonal variations and longer term trends of groundwater level beneath pasture;

(iii) determine the effect of agroforestry on groundwater level;

(iv) identify the groundwater flow direction and any change due to the agroforestry treatment; and

(v) determine spatial and temporal variability in groundwater salinity under pasture and agroforestry.

4. PLANTATION ESTABLISHMENT AND MANAGEMENT

4.1 Plantation Establishment and Layout

The agroforestry site consists of 4 blocks occupying an area of 4.5 ha. Four species of eucalyptus were planted on these blocks in 1978. The percentage of each block planted with each species type is shown in Table 1.

4.2 Plantation Management

In Table 1, the thinning history of the agroforestry trial is shown. In May 1981, every third row of trees was removed in blocks A, B and D. The stem density achieved by this process was 660 sph (stem per hectare) on all three blocks. Block C was not thinned.

In February 1982, final thinning of trees took place leaving stem densities ranging from 150 to 900 sph (Table 1). The tree diameters at breast height over bark (DBHOB) were measured in November 1983.

4.3 Crown Cover

Crown cover is defined as the percentage of the ground area covered by the vertical projection of the vegetation canopy on the ground surface. Measurements of crown cover of the plantations within the agroforestry site were taken on the 9th of December, 1987 using a crownometer similar to the one described by Montana and Ezcurra (1980). The range of crown cover was 20% to 31% with an average of 25%.

4.4 Pasture Management

The site was left ungrazed for 2 years following planting. Sheep grazing recommenced in 1980. Fertilisers were used to overcome superphosphate deficiency. Once grazing commenced, there was a general improvement in pasture production.

5. HYDROLOGICAL DATA COLLECTION

5.1 Rainfall Data

Rainfall records were taken from pluviometer M509374 located approximately 700 m east of the catchment boundary (Fig. 1). For periods of missing rainfall, data from the nearest pluviometer (M509337) were transposed using the regression equation derived from Fig. 3. During the study period (1982-89) only 8% of the record from pluviometer M509374 was missing. The long term average rainfall (1926-86) for the study site was estimated at 722 mm yr^{-1} (Hayes and Garnaut, 1981; Bell et al., 1990). This estimate was extended to 1988 using the pluviometer data to give 713 mm yr^{-1}.

5.2 Groundwater Monitoring

The groundwater bore network for the control site is shown in Fig. 1 and for the agroforestry site in Fig. 2. The pasture control bores are located at the upper mid-slope of the control site (Fig. 1). All control bores were drilled to bedrock and had slotted lengths varying from 6 m to 18 m (Table 2a).

Sixteen bores were installed at the agroforestry site. In each block, two pairs of bores were drilled. Each pair consisted of one shallow (2 m deep) and one deep (more than 4 m) bore. Each bore had a one metre screen at the base (Table 2b).

All bores were monitored for water level and salinity once a month between 1982 and 1989. Some of the samples collected were chemically tested and their ionic concentrations and electrical conductivity (ms m^{-1}) were measured. Salinity (Total Soluble Salts, TSS) was determined by summing the major ions. A relationship between TSS (mg L^{-1}) and electrical conductivity (mS m^{-1}) was derived (Fig. 4).

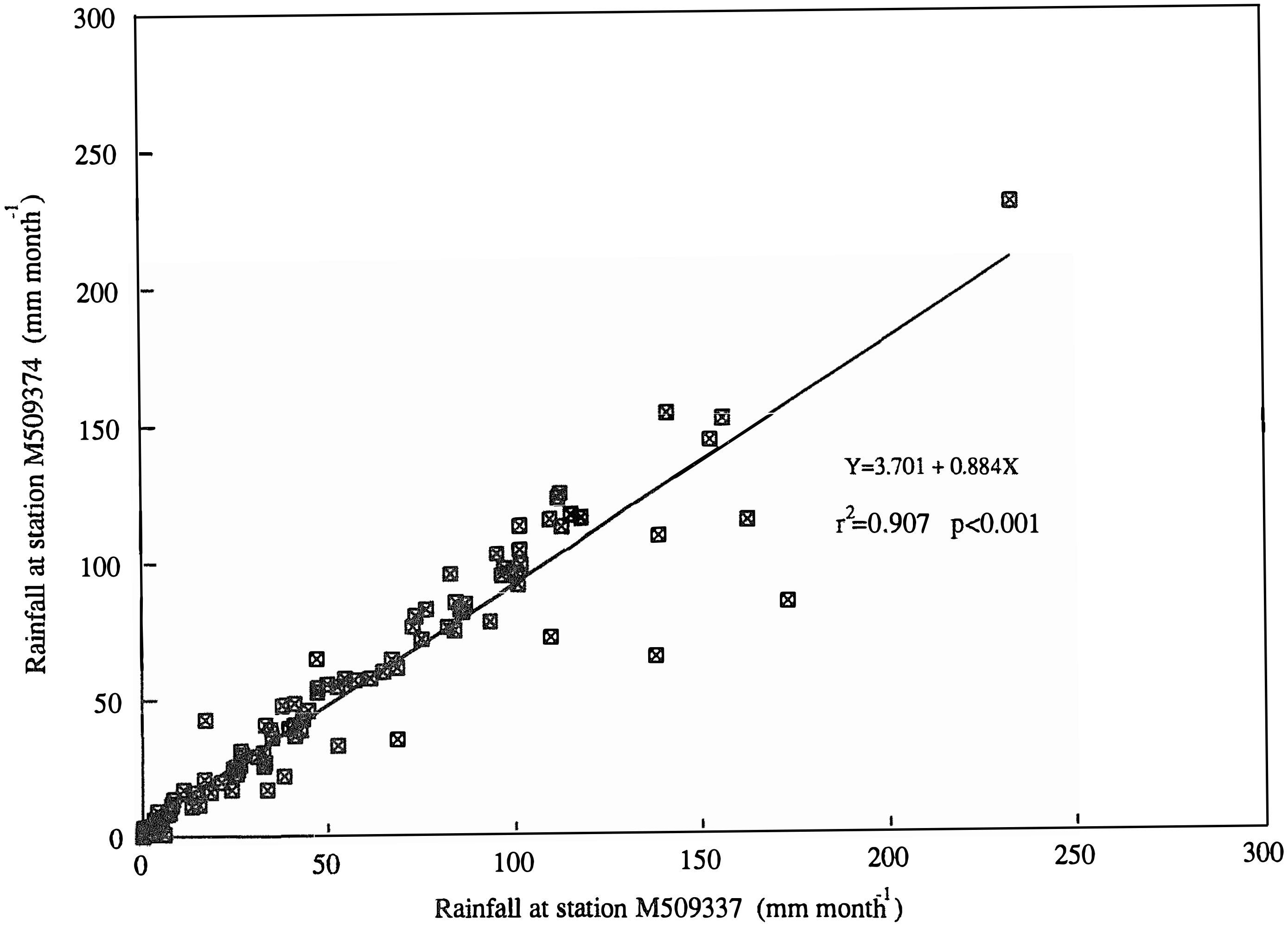


Figure3 : Correlation between two rainfall stations

Table 2a : Details of observation bores - pasture

S.W.R.I.S. Bore Number	Drillers Bore Number	Commencement Of Operation	Bore Classif- ication	Top of Inner Tube (AHD)	Natural Surface Level (AHD)	Bottom Of Tube (AHD)	Length of Slotting (m)	Length of Inner Tube (m)	Height of (1) T.O.I.T. Above N.S.L. (m)	Depth of (2) B.O.T. Below N.S.L. (m)
61218008	8-76	01/06/1976	Pasture	295.767	295.090	274.677	18.00	21.09	0.677	20.413
61218009	9-76	01/06/1976	Pasture	291.092	290.400	274.432	14.00	16.66	0.692	15.968
61218038	22-77	30/07/1977	Pasture	284.607	284.020	266.22	6.00	18.39	0.587	17.800
61218044	29-77	30/07/1977	Pasture	287.460	286.860	271.36	8.50	16.10	0.600	15.500
61218045	30-77	30/07/1977	Pasture	285.512	284.880	267.38	11.00	18.13	0.632	17.500

Table 2b : Details of observation bores - agroforestry

S.W.R.I.S. Bore Number	Drillers Bore Number	Commencement Of Operation	Bore Classif- ication	Top of Inner Tube (AHD)	Natural Surface Level (AHD)	Bottom Of Tube (AHD)	Length of Slotting (m)	Length of Inner Tube (m)	Height of T.O.I.T. Above N.S.L. (m)	Depth of B.O.T. Below N.S.L. (m)
61219081	A1/81S	13/03/1981	Reforest	276.600	275.800	274.600	1.00	2.000	0.800	1.200
61219082	AS1/81D	13/03/1981	Reforest	276.300	275.800	265.450	1.00	10.850	0.500	10.350
61219083	A2/81S	12/03/1981	Reforest	2780.010	269.210	268.010	1.00	2.000	0.800	1.200
61219084	A2/81D	12/03/1981	Reforest	269.690	269.210	265.510	1.00	4.180	0.480	3.700
61219085	B1/81S	13/03/1981	Reforest	272.920	272.120	270.920	1.00	2.000	0.800	1.200
61219086	B1/81D	13/03/1981	Reforest	272.620	272.120	264.920	1.00	7.700	0.500	7.200
61219087	B2/81S	12/03/1981	Reforest	269.790	269.020	267.740	1.00	2.050	0.770	1.280
C1219088	b2/81d	12/03/1981	Reforest	269.520	269.020	264.820	1.00	4.700	0.500	4.200
61219089	C1/81S	13/03/1981	Reforest	271.210	270.450	269.170	1.00	2.040	0.760	1.280
61219090	C1/81D	13/03/1981	Reforest	270.950	270.450	264.100	1.00	6.850	0.500	6.350
61219091	C2/81S	14/03/1981	Reforest	269.150	268.350	267.120	1.00	2.030	0.800	1.230
61219092	C2/81D	14/03/1981	Reforest	268.960	268.350	262.840	1.00	6.120	0.610	5.510
61219093	D1/82S	16/03/1981	Reforest	270.220	269.420	268.220	1.00	2.000	0.800	1.200
61219094	D1/81D	16/03/1981	Reforest	269.920	269.420	263.800	1.00	6.120	0.500	5.620
61219095	D2/81S	16/03/1981	Reforest	269.040	268.240	267.040	1.00	2.000	0.800	1.200
61219096	D2/81D	16/03/1981	Reforest	268.740	268.240	264.040	1.00	4.700	0.500	4.200

(1) T.O.I.T. = top of inner tube

(2) B.O.T. = bottom of tube

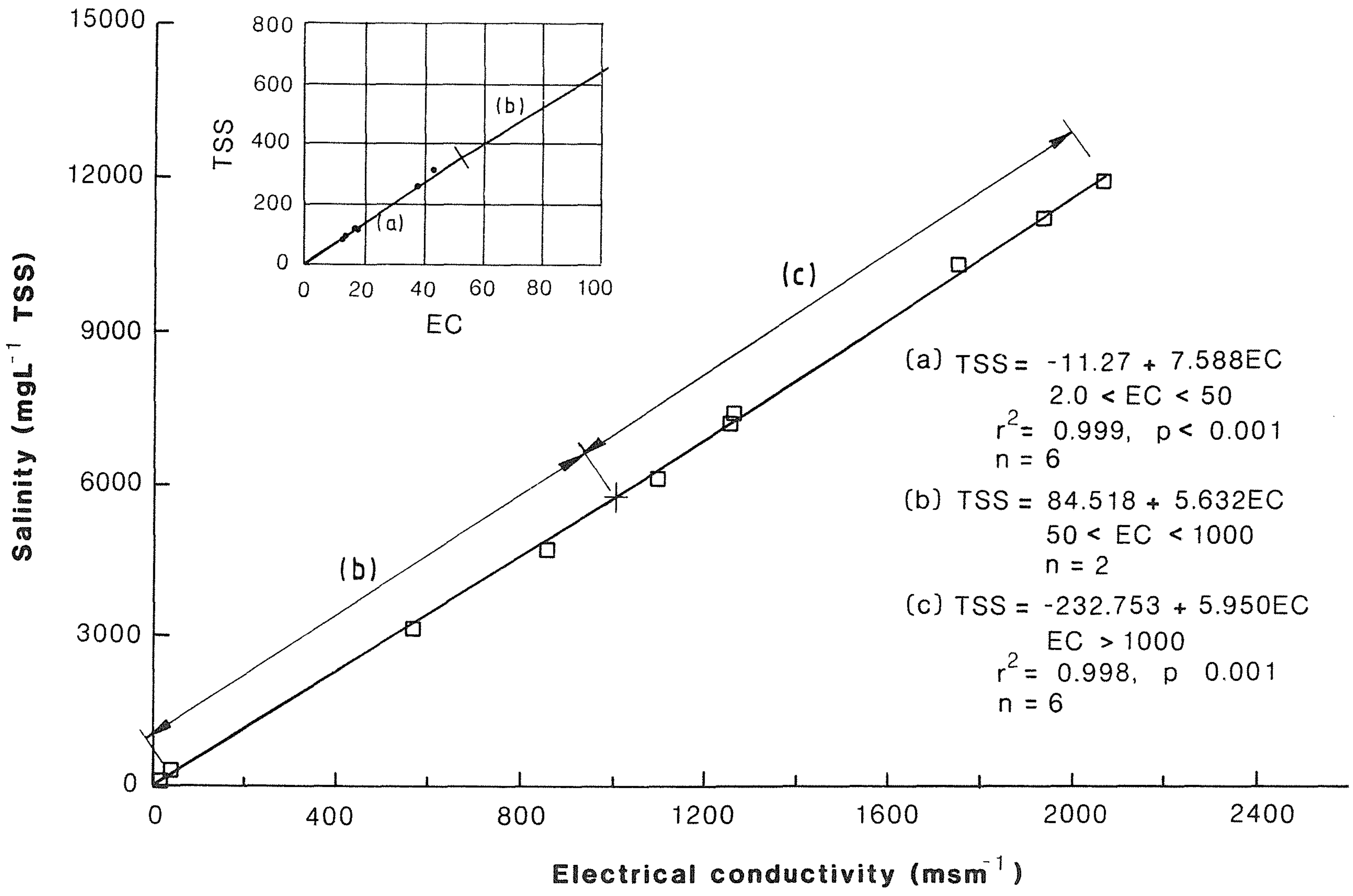


Figure 4:Relationship between Electrical Conductivity and Total Soluble Salts

6. DATA ANALYSES AND INTERPRETATION OF RESULTS

6.1 Rainfall

Annual rainfall has been analysed in terms of the hydrological water year, i.e. April to March. Over the study period (1982-89), rainfall varied between from 470 mm yr^{-1} to 910 mm yr^{-1}. The average for the period of 617 mm yr^{-1} was 13% lower than the long term average (1926-88) of 713 mm yr^{-1}. Only three years (1981, 1983 and 1988) had rainfall higher than the long term average. Most of the rainfall (more than 80%) occurred between May and October.

6.2 Groundwater Levels under Pasture

Hydrographs for the five bores at the control site are shown in Appendix A. The hydrographs of all five bores have also been plotted together on the one graph to show the similarity in trends (Fig. 5).

The annual minimum groundwater levels of all pasture bores are given in Table 3a. The average variation of yearly minimum groundwater level in all five bores, relative to the 1982 minimum, is shown in Fig. 6. In 1984 and 1989 groundwater levels increased as a result of high rainfall in the preceding year, but declined in all other years. During 1982-89 there was a net rise of 0.35 m.

The annual maximum groundwater levels for all pasture bores are given in Table 3b. The yearly maximum groundwater level showed similar rises in the high rainfall years of 1983 and 1988 and falls in the other years. Over the period 1982-89 there was a net rise in maximum groundwater level of 0.48 m.

Linear regressions were developed to predict the change in groundwater levels under different rainfall conditions.

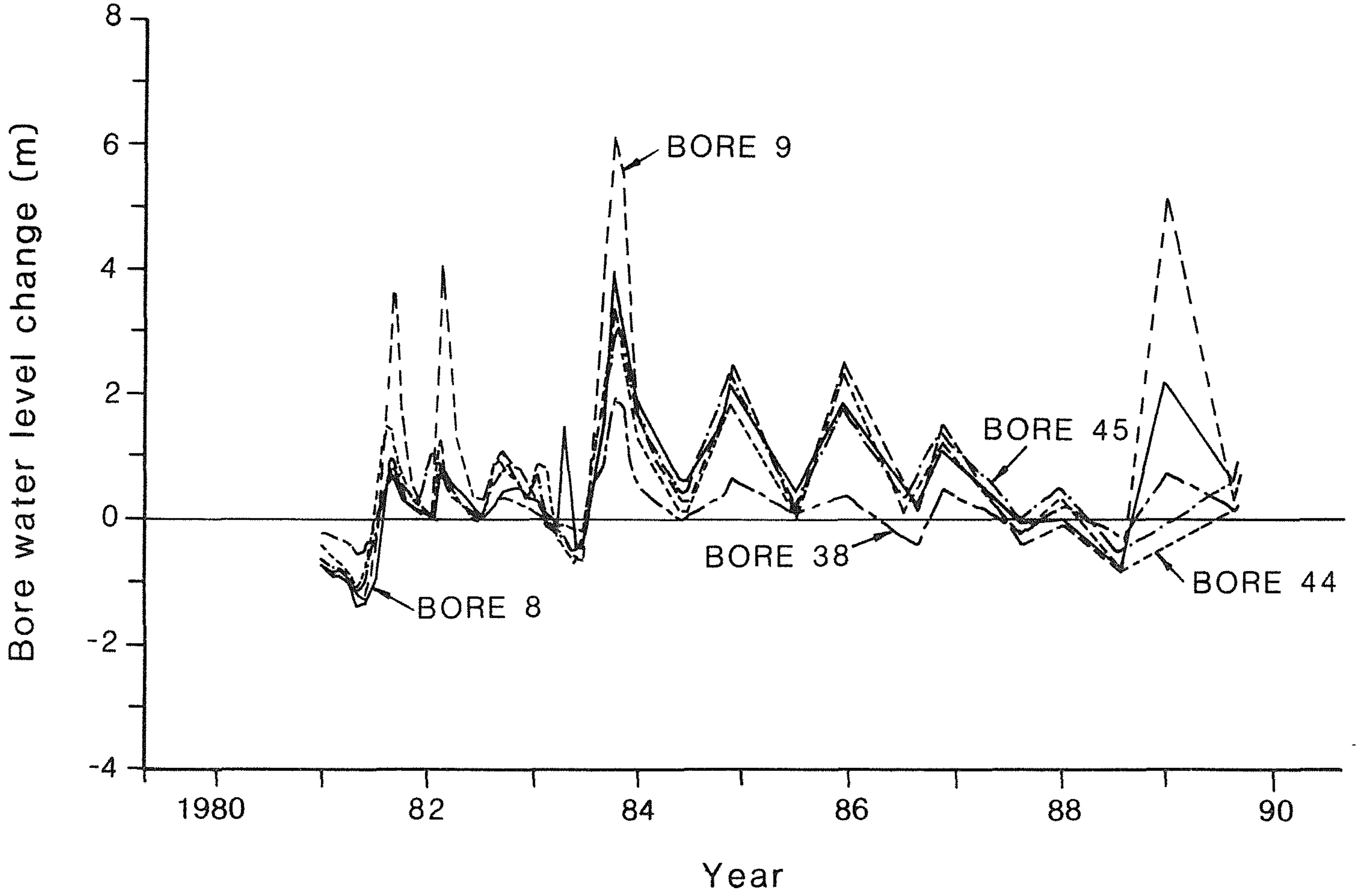


Figure 5:Groundwater levels at pasture site relative to 1982 minimum level

Table 3a: Yearly minimum groundwater levels (m AHD) of all pasture bores

Bore No.	1982	1983	1984	1985	1986	1987	1988	1989
G61218008	283.157	282.677	283.767	283.587	283.387	283.117	282.387	283.767
G61218009	281.172	280.522	281.462	281.272	281.302	280.792	280.332	281.492
G61218038	276.297	276.097	276.297	276.367	275.907	276.057	276.007	276.407
G61218044	278.820	278.160	278.980	278.880	278.940	278.610	278.010	278.960
G61218045	280.942	280.452	281.362	281.162	281.342	280.962	280.412	281.512

Table 3b: Yearly maximum groundwater levels (m AHD) of all pasture bores

Bore No.	1982	1983	1984	1985	1986	1987	1988	1989
G61218008	283.997	287.087	285.297	285.027	284.267	283.167	285.357	285.267
G61218009	285.242	287.302	283.662	283.682	282.742	281.092	281.342	284.942
G61218038	277.157	278.257	276.947	276.657	276.807	276.507	277.057	277.207
G61218044	280.060	282.250	280.700	281.210	280.060	279.160	278.010	280.460
G61218045	281.982	284.052	283.272	282.702	282.362	281.462	280.412	282.962

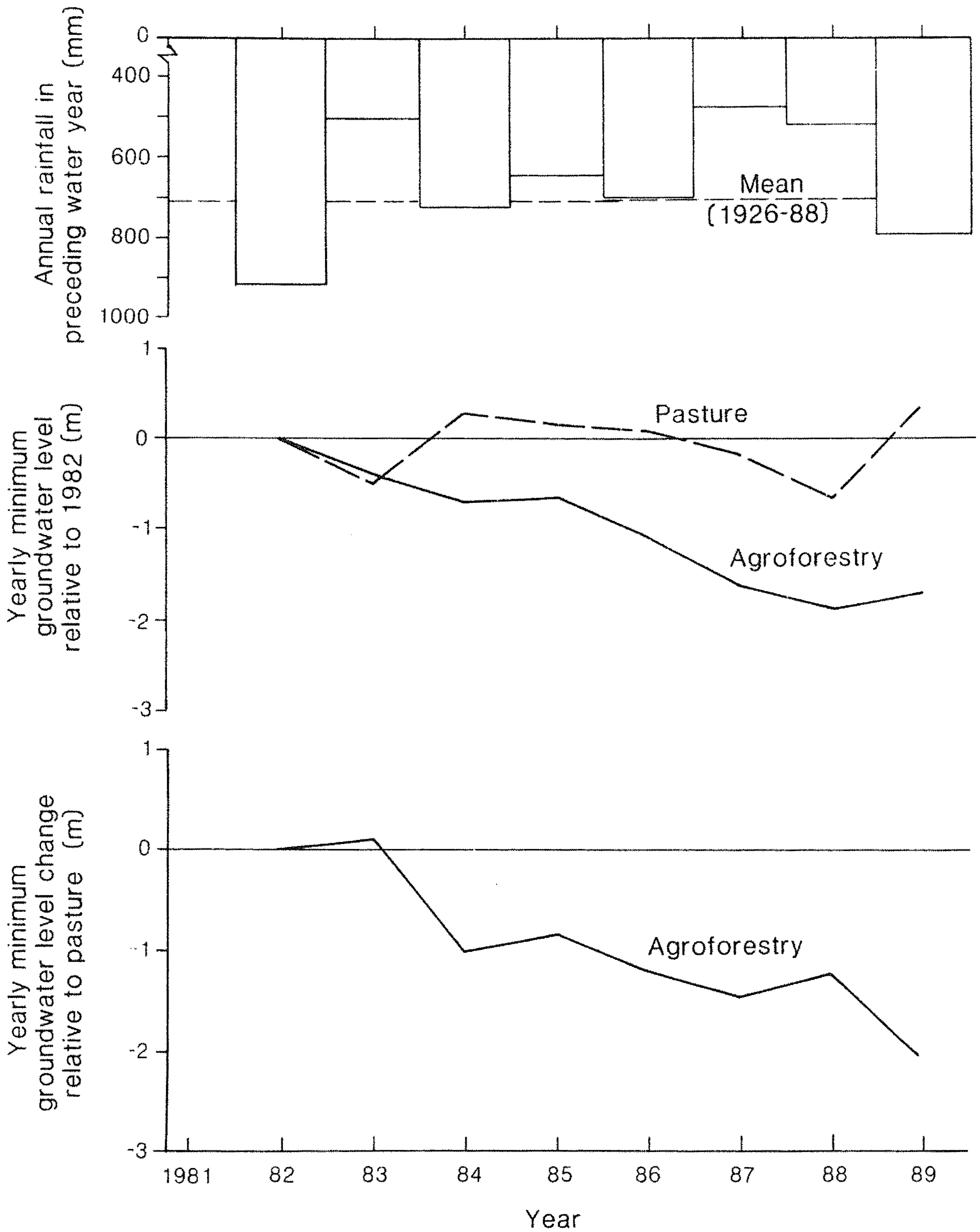


Figure 6:Annual rainfall and minimum groundwater level at the agroforestry site

The minimum groundwater level occurs in autumn. This level is strongly influenced by the rainfall of the preceding year. A linear regression of change in minimum groundwater level (y, mm yr^{-1}) relative to the previous year's annual rainfall (x, mm) has the form:

$$y = -2409 + 3.97X \text{ (mm)} \qquad (1)$$
$$r^2 = 0.83, \; p \sim 0.001$$

Equation (1) predicts minimum groundwater levels would rise 420 mm yr^{-1} under long term rainfall conditions; and would be stable if the preceding year's rainfall was 607 mm (Fig. 7a).

As the maximum groundwater level occurs soon after the winter rains (in the same year), the annual change in maximum groundwater level (y, mm yr^{-1}) was plotted against the rainfall of the same year (x,mm). The regression is:

$$y = -3263 + 5.17X \text{ (mm)} \qquad (2)$$
$$r^2 = 0.175, \; p \sim 0.3$$

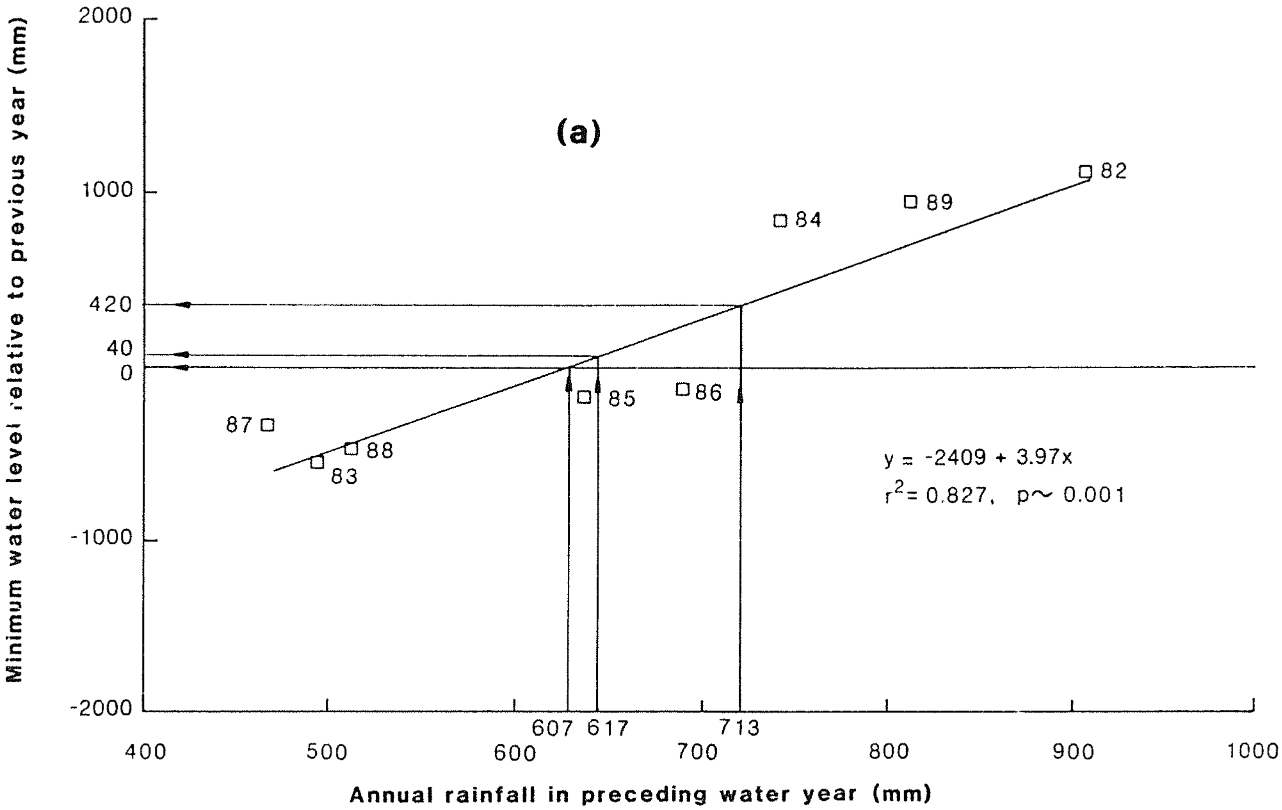
The low r^2 and p indicate that equation (2) would be a poor predictor for maximum groundwater level change (Fig. 7b).

6.3 Groundwater Level Response to Reforestation

Trees planted on agricultural pastures have the potential to decrease the vertical recharge to the aquifer system by increasing transpiration and interception loss (Eastham et al., 1988; Schofield, 1990a). Analyses of annual minima and maxima and comparisons to the control site were carried out to determine the effects of agroforestry on groundwater levels. A typical representation of groundwater level reduction due to reforestation is shown in Fig. 8.

6.3.1 **Minimum Groundwater Level**

The annual minimum groundwater levels of all agroforestry bores are shown in Table 4a.



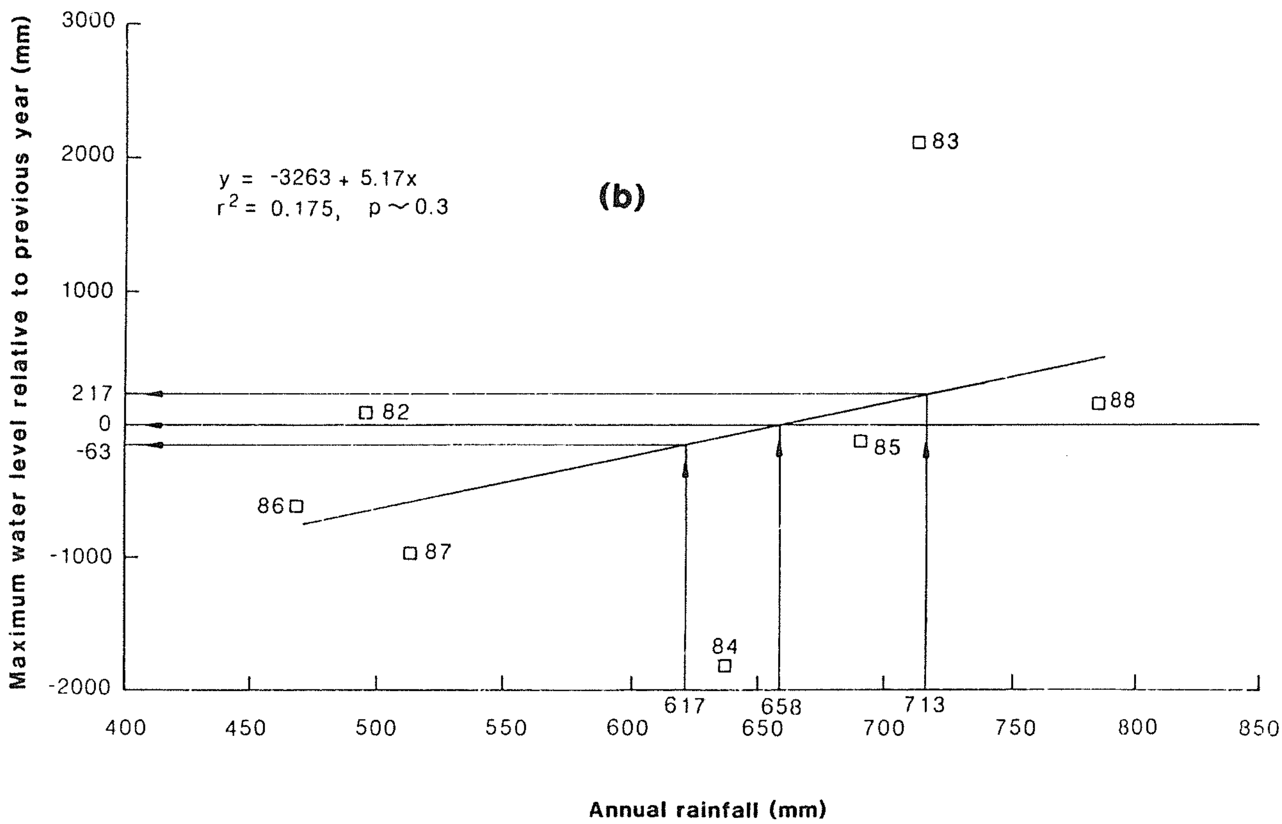


Figure 7:Relationship between groundwater level and annual rainfall --- pasture bores (a) minimum, (b) maximum

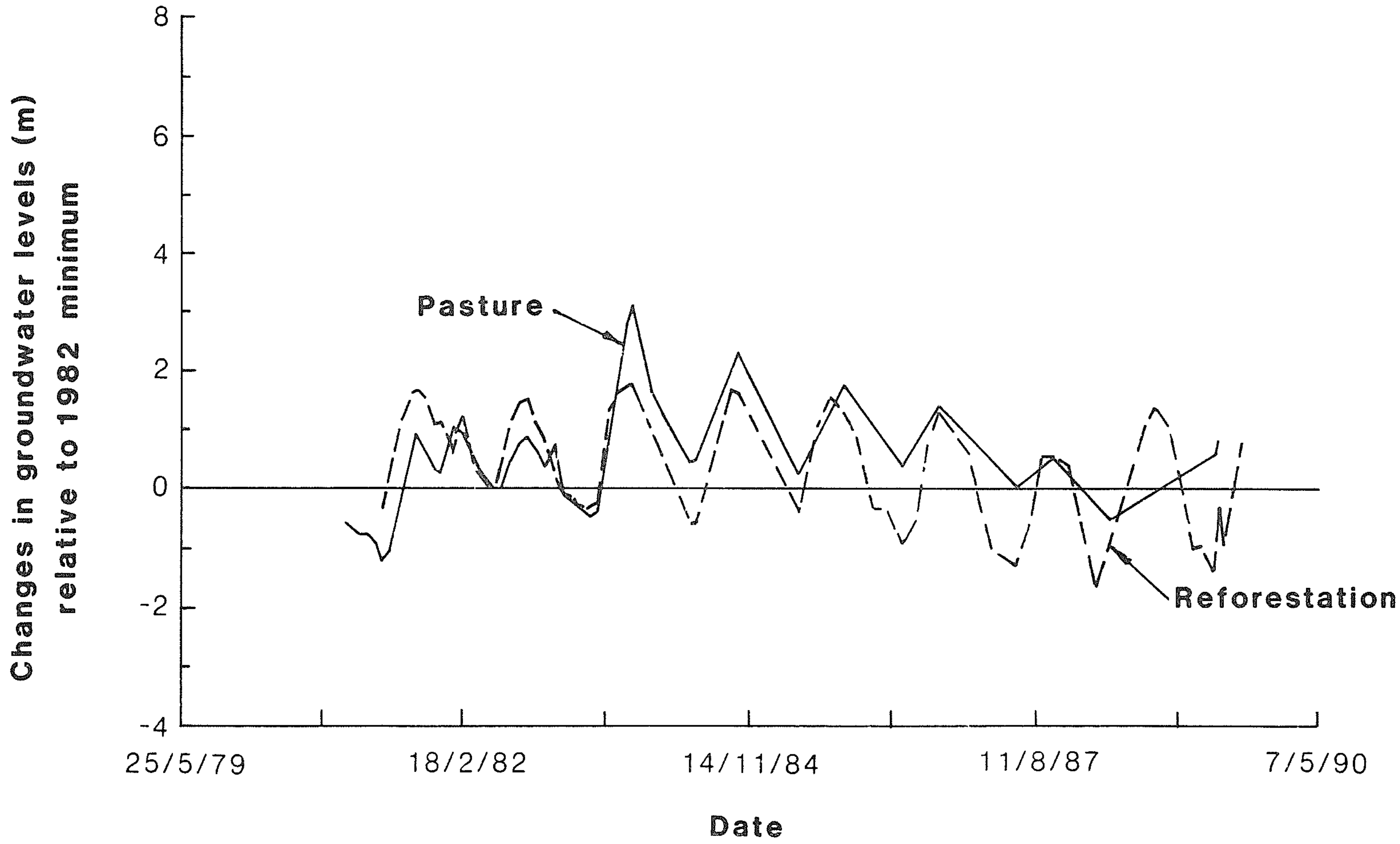


Figure 8:Typical groundwater hydrographs at pasture and agroforestry sites

The changes in annual minimum groundwater level for the agroforestry and control sites relative to the levels recorded in 1982 are plotted in Fig. 6. The plots show that due to very low rainfall in 1982 (497 mm) the water level under the control and agroforestry sites in 1983 fell 0.50 m and 0.38 m, respectively. The relative rise in water level under agroforesty was 0.12 m. In 1984, following a year of near average rainfall (715 mm), the groundwater level under the agroforestry site dropped 1.0 m relative to the control site. The annual rainfall, from 1985 to 1988, was lower than the long term average ranging from 470 mm to 693 mm. During this period, groundwater level, both under pasture and reforestation had near-uniform decline. Fig. 6 shows that water level under agroforestry increased slightly relative to pasture in 1985 and 1988. In 1988 the annual rainfall was greater than the long term average. This resulted in water level rising under both pasture and agroforestry in 1989. At the end of the study period (1989) the absolute reduction in the average minimum groundwater level under agroforestry was 1.7 m. The reduction relative to the control site was 2.0 m.

6.3.2 **Maximum Groundwater Level**

The yearly maximum groundwater levels of agroforestry bores are given in Table 4b.

The maximum water level under agroforestry and the control site are compared in Fig. 9. In 1983, groundwater level under the control site rose 2.1 m, but surprisingly at the agroforestry site the increase was only 0.15 m. This resulted in a net decline of 1.95 m under agroforestry. However, this sharp decline did not continue in the ensuing period. In 1984, the water level under pasture dropped 1.8 m compared to 1983. From 1984 to 1987, the declines in water levels at both the control and agroforestry sites were closely matched. By the end of study period (1989) the average maximum groundwater level reduction under agroforestry relative to the control was 1.1 m.

Table 4a: Yearly minimum groundwater level (m AHD) of all agroforestry bores

Bore No.	1982	1983	1984	1985	1986	1987	1988	1989
G61219082	271.590	270.770	270.240	269.850	269.150	268.000	267.300	267.600
G61219084	267.010	266.660	266.360	266.490	266.020	265.590	265.590	265.490
G61219088	267.040	266.710	266.440	266.620	266.130	265.720	265.370	265.620
G61219090	269.260	268.520	268.240	268.300	268.120	267.700	267.700	268.150
G61219092	266.700	266.220	265.950	266.110	265.730	265.490	265.210	265.360
G61219094	266.720	266.300	266.200	266.220	265.990	265.620	265.420	265.720
G61219096	265.500	265.990	265.570	265.800	265.150	264.490	264.290	264.140

Table 4b: Yearly maximum groundwater level (m AHD) of all agroforestry bores

Bore No.	1982	1983	1984	1985	1986	1987	1988	1989
G61219082	273.550	273.080	272.710	271.810	271.170	270.450	270.350	270.700
G61219084	268.740	269.010	268.890	268.750	268.540	267.590	268.730	268.590
G61219088	268.580	268.840	268.730	268.600	268.370	267.570	268.420	268.17
G61219090	270.230	270.420	270.250	270.135	269.950	269.600	269.930	269.25
G61219092	267.990	268.220	268.080	267.990	267.810	267.110	267.760	267.560
G61219094	267.980	268.340	268.180	268.110	267.820	267.170	267.920	267.520
G61219096	267.720	267.930	267.970	267.920	267.840	267.290	267.310	267.940

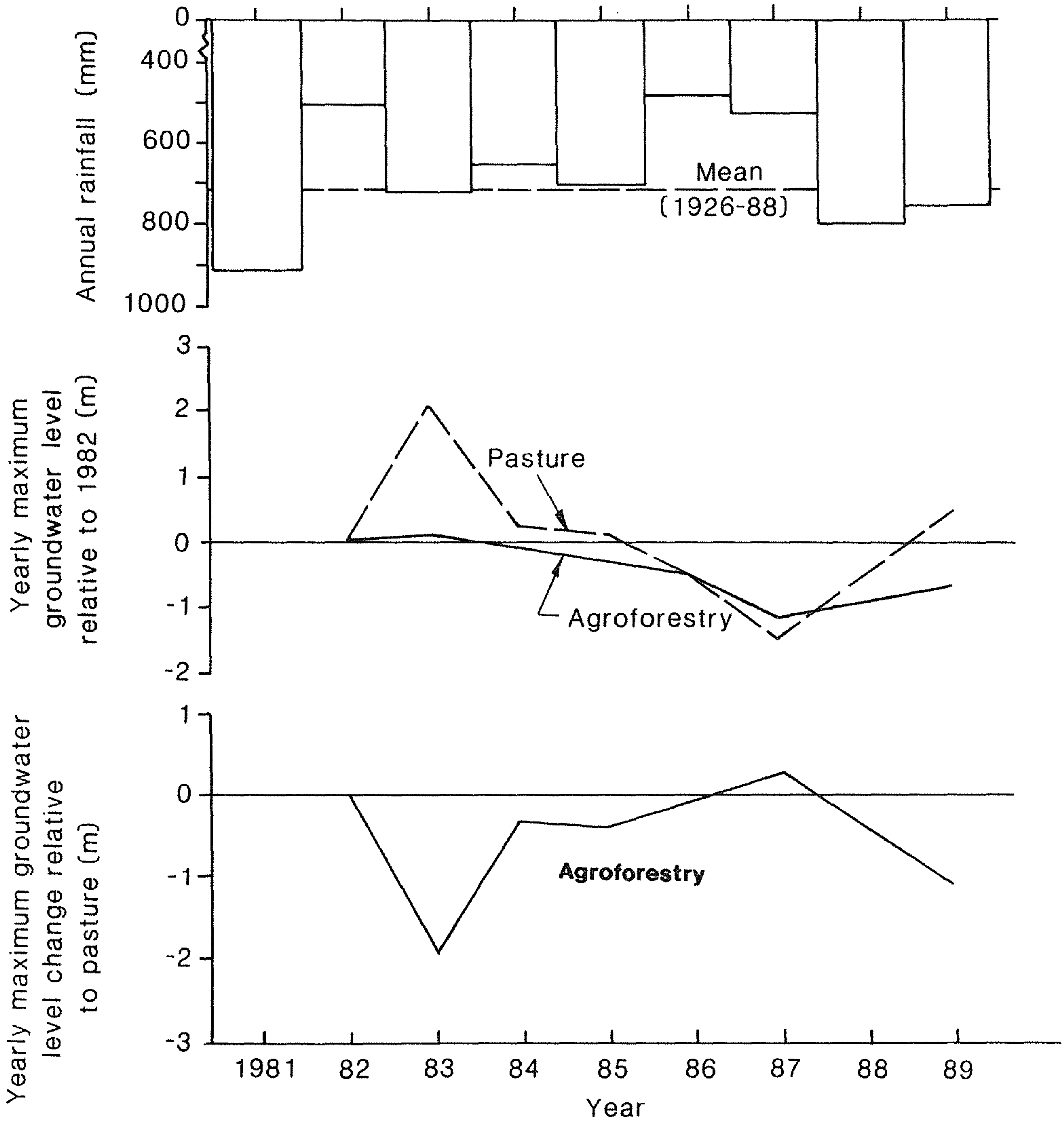


Figure 9:Annual rainfall and maximum groundwater level at the agroforestry site

6.3.3 Comparison of Minimum and Maximum Groundwater Level Changes

The changes in yearly minimum and maximum water levels relative to the pasture are shown in Fig. 10. In 1983 the minimum groundwater level rose slightly, but the maximum groundwater level declined 2.1 m. From 1984 to 1979, the minimum water level reduction was near-linear, while the maximum closely matched the changes in pasture level.

6.3.4 Regression Analyses

Linear regressions were developed to predict the changes in minimum and maximum groundwater levels under different annual rainfall conditions.

For minimum groundwater levels, the annual change relative to the previous year (y, mm yr $^{-1}$) was plotted against the rainfall of the preceeding year (x, mm). The equation was:

$$y = -1139 + 1.47X \text{ (mm)} \qquad (3)$$
$$r^2 = 0.57, \; p\tilde{}0.001$$

This regression predicts a 90 mm yr^{-1} fall in minimum groundwater level under long term average rainfall (713 mm yr^{-1}) conditions. For the minimum groundwater level to decrease the rainfall of the preceding year would be less than 772 mm (Fig. 11a).

As the maximum groundwater levels occurred soon after the winter rains, the annual change relative to the previous year (y, mm yr^{-1}) was plotted against the annual rainfall (x, mm) of the same year. The best fit line was:

$$y = -1443 + 2.18X \text{ (mm)} \qquad (4)$$
$$r^2 = 0.53, \; p\tilde{}0.01$$

The above equation predicts a 110 mm yr^{-1} rise in maximum groundwater level if the annual rainfall equalled the long term average. The maximum groundwater level would be stable if the annual rainfall is 662 mm (Fig. 11b).

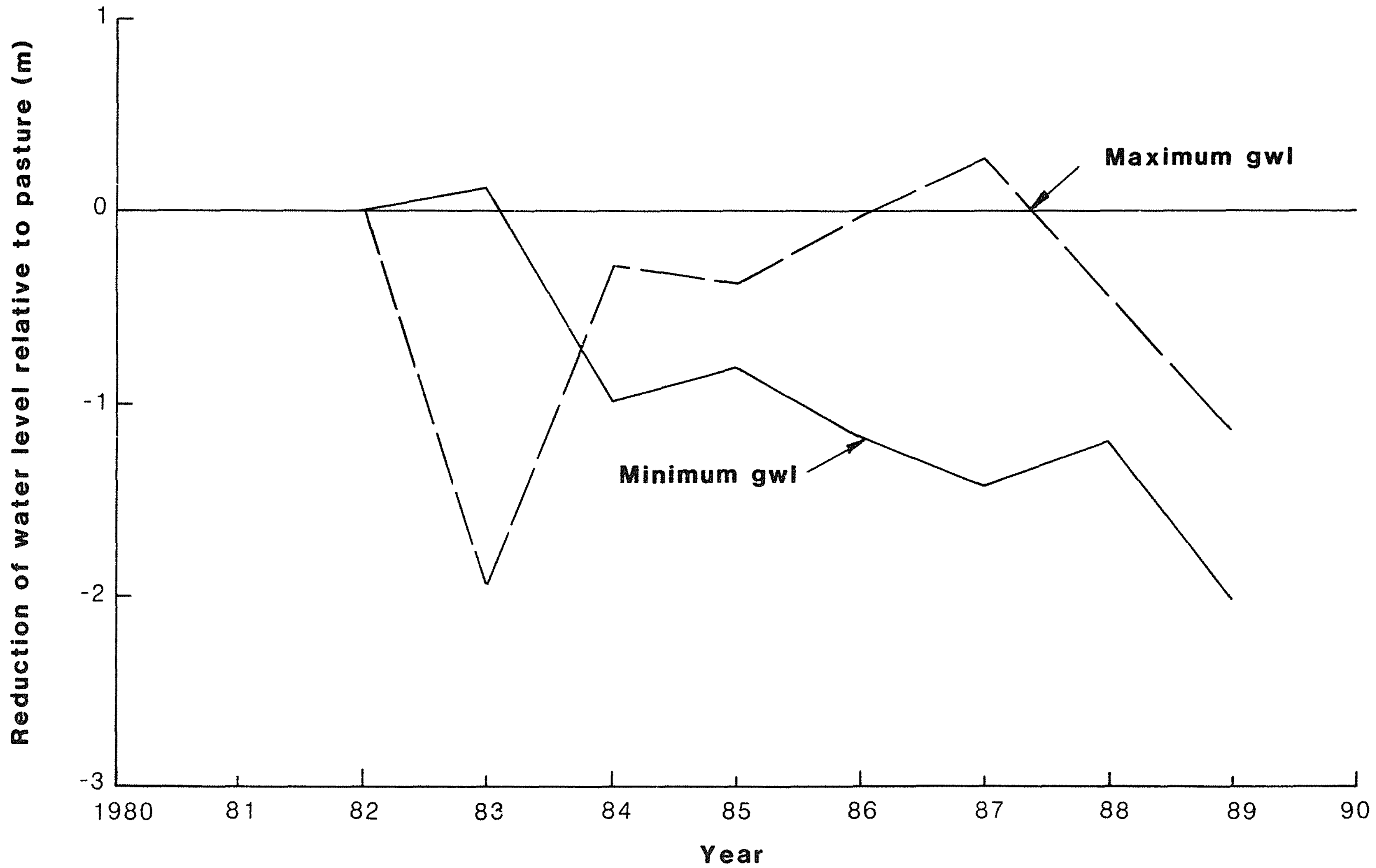
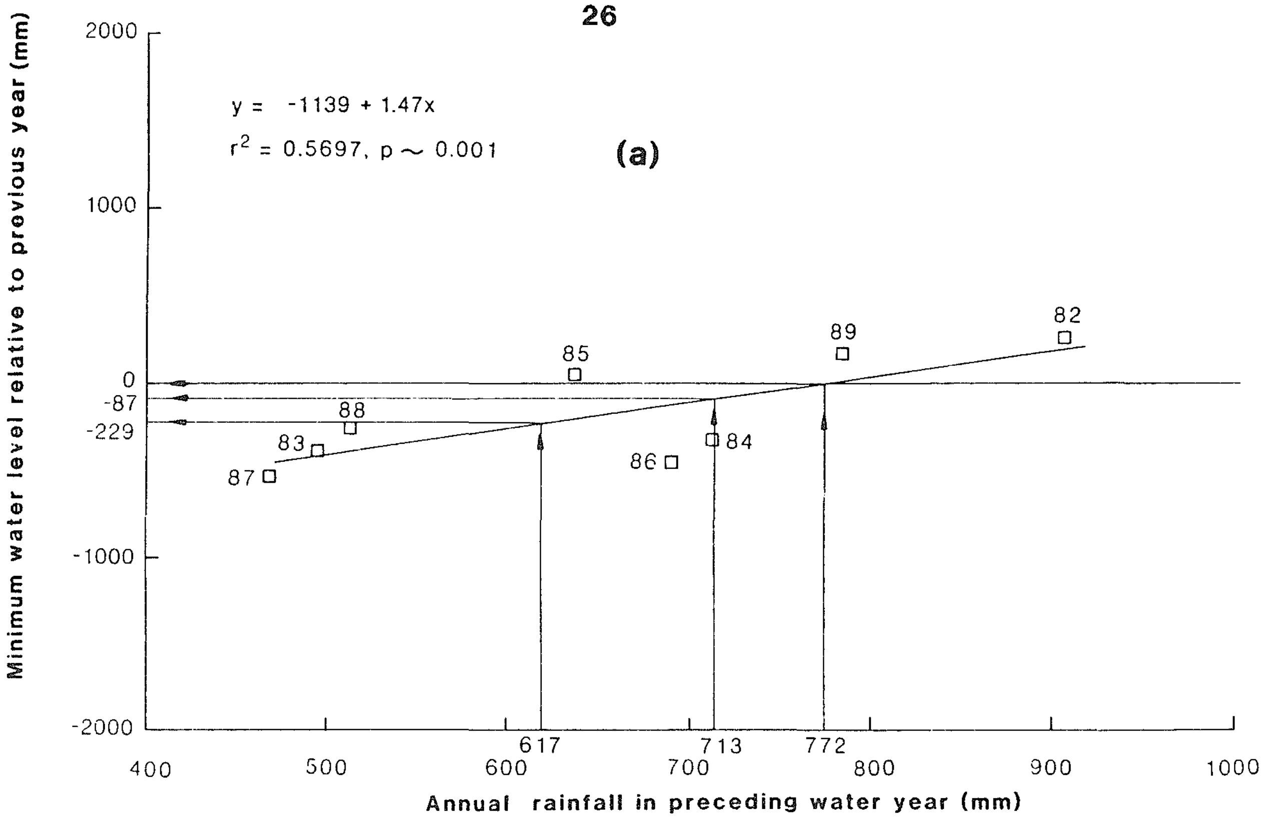


Figure 10:Comparison of the reduction of minimum and maximum groundwater level relative to pasture



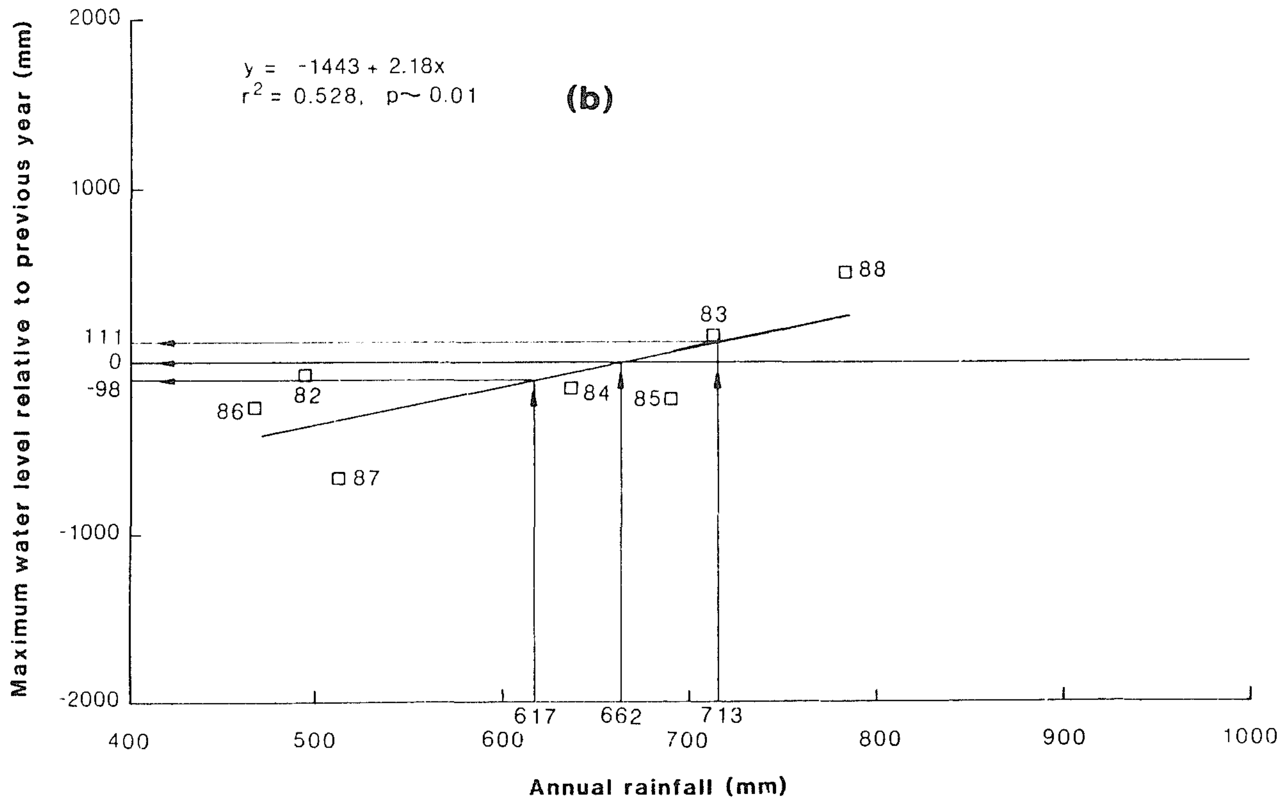


Figure 11:Relationship between groundwater level and annual rainfall --- agroforestry bores (a) minimum, (b) maximum

6.4 Effect on Topography and Stem Density on Water Table

Fig. 12 presents the minimum groundwater level reduction of reforested bores relative to 1982. The natural ground surface elevations of bores 61218082 and 61218086 are approximately 6 and 3 m higher than the other bores which are located on the flat valley floor (Fig. 2). The higher elevations of these two bores appeared to induce a more rapid water table decline than the other bores. Fig. 12 shows that except those two bores, the groundwater level reduction of other bores are closely matched. This close association of change in groundwater level suggests the effects of different stem densities on groundwater level reduction cannot be assessed at this site.

6.5 Groundwater Flow

Minimum and maximum groundwater potentiometric contours for the beginning and the end of the study (May and September '82, September '88 and May '89) are shown in Fig. 13. The following features of the groundwater system beneath the agroforestry site were identified:

(i) The direction of groundwater flow is generally north to north-west, from upslope towards the stream line.

(ii) The flow direction for maximum and minimum groundwater levels was more or less the same.

(iii) Although reforestation lowered the minimum groundwater table the overall flow direction remained practically unchanged.

6.6 Groundwater Salinity Trends under Pasture

The groundwater salinities of all pasture bores are shown in Appendix A. The temporal variation in salinity in most bores was high and erratic. The marked change from one observation to the next (up to five-fold) indicates the data is suspect. By comparison, results from another experimental pasture control

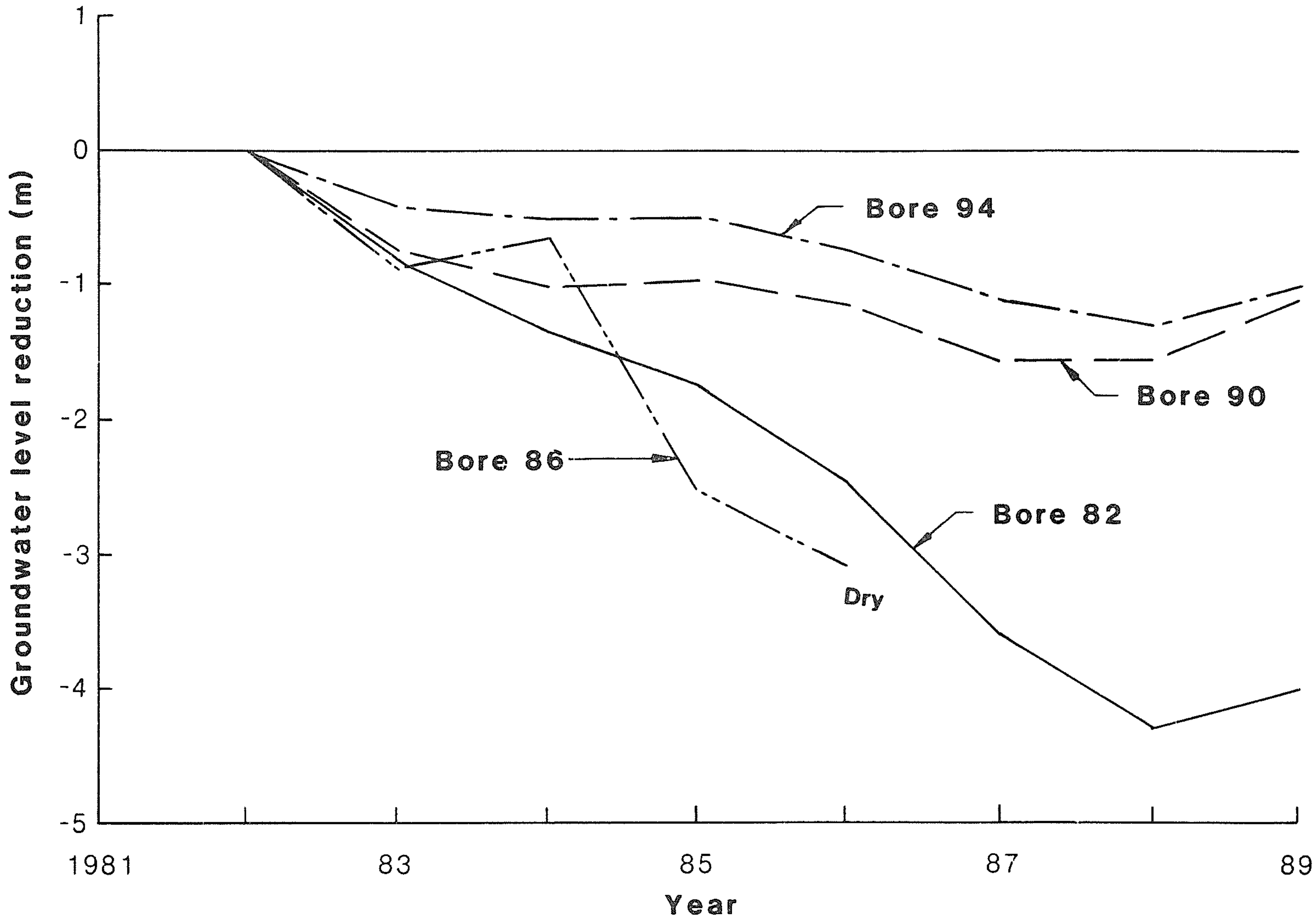


Figure 12:Groundwater hydrographs --- agroforestry bores

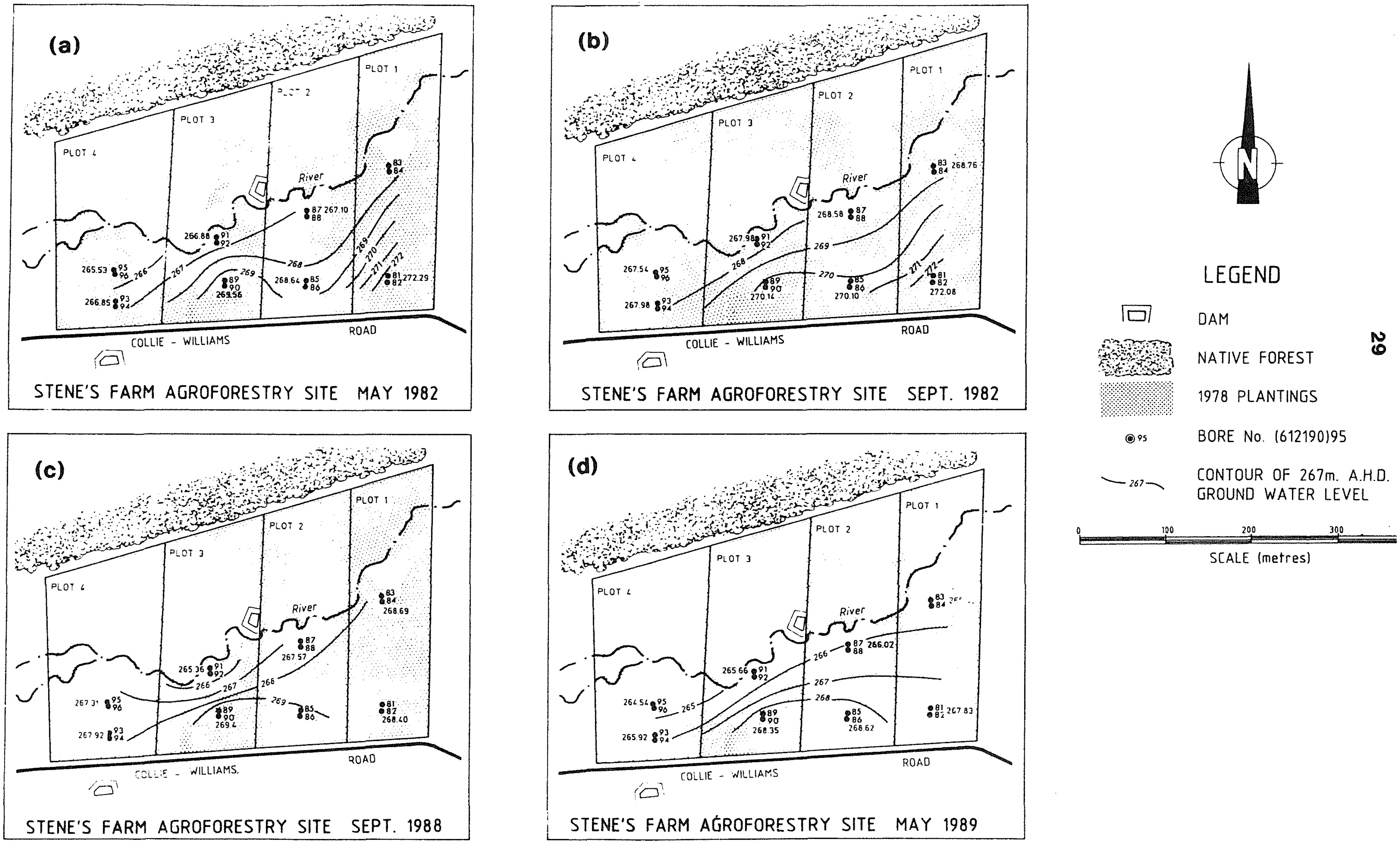


Fig. 13 :Regional groundwater levels and flow directions

(Bari et al., 1990) showed large variations in salinity, but smaller changes between observation events. This further points to the data at Stene's pasture control as being unreliable.

Salinity data from five control bores were analysed into three categories.

(a) All bores
(b) Fresh bores
(c) Saline bores

The results of the pumped samples taken on 16/5/89 are compared with results of those taken on 6/5/82. Table 5 indicates the average reduction in groundwater salinity of all bores was 44%. The change in salinity in individual bores, varied from a rise of 54% to a fall of 51%. The saline bore group had similar changes, and the fresh bores which had a 2% increase in average salinity.

6.7 Groundwater Salinity Trends under Agroforestry

The groundwater salinities of all agroforestry bores are shown in Appendix A. Like the control site, the variation in salinity was more than five-fold within a few months. So, all the bores were pumped and developed in May 1989, than sampled and analysed.

The agroforestry bores were also classified into three groups.

(a) All bores
(b) Bores screened at water table
(c) Bores screened below water table

The results of the pumped samples taken on 30/5/89 were compared with results of those taken on 7/5/82. Table 6 indicates the average reduction in groundwater salinity of all bores was 6%. Three bores had an increase in salinity ranging from 18% to 283%, while the others had a decline, varying from 3% to 50%. The bore group screened at the water table had a 6% rise. The group screened below the water table had a 25% reduction.

Table 5 : Comparison of May '80 salinity of all pasture bores with that of May '89

Bore set		Salinity ($mg\ L^{-1}$) on 06/05/80		Salinity ($mg\ L^{-1}$) 30/05/89		% Change in salinity	
Classification	Bore no.		Average		Average		Average
All	61218008	273.00		210.00		-23	
	61218009	132.00		203.00		53.79	
	61218038	3645.00		1776.00		-51.28	
	61218044	4587.00	2412.6	2828.00	1429.4	-38.35	-44.19
	61218045	3426.00		2130.00		-37.83	
Fresh	61218008	273.00		210.00		-23	
	61218009	132.00	202.50	203.00	206.50	53.79	1.97
Saline	61218038	3645.00		1776.00		-51.28	
	61218044	4587.00	3886.00	2828.00	2244.67	-38.35	-42.22
	61218045	3426.00		2130.00		-37.83	

Table 6 : Comparison of May '80 salinity of agroforestry bores with that of May '89

Bore set		Salinity ($mg\ L^{-1}$) on 06/05/80		Salinity ($mg\ L^{-1}$) 30/05/89		% Change in salinity	
Classification	Bore no.		Average		Average		Average
All	61219082	445.00		1742.00		282.86	
	61219084	3543.00		3453.00		-2.54	
	61219088	6252.00		9358.00		49.68	
	61219090	9882.00	6498.14	4951.00	6135.57	-49.90	-5.58
	61219092	6603.00		5990.00		-9.28	
	61219094	11506.00		8894.00		-22.70	
	61219096	7246.00		8561.00		18.15	
Screened	61219084	3543.00		3453.00		-2.54	
at water	61219088	6252.00	7136.75	9358.00	7571.5	49.68	6.1
table	61219094	11506.00		8894.00		-22.70	
	61219096	7246.00		8561.00		18.15	
Screened	61219082	445.00		1742.00		282.86	
below	61219090	9882.00	5643.33	4951.00	4227.67	-49.90	-25.10
water table	61219092	6603.00		5990.00		-9.28	

7. DISCUSSION

7.1 Rainfall and Groundwater Level Reduction

The average annual rainfall during the study period (1982-89) was 13% lower than the long term average (1926-88). If long term average rainfall conditions had prevailed, regression analysis indicated groundwater levels would have risen at the control (pasture) site. At the agroforestry site, the maximum groundwater level would have risen while the minimum level would have fallen. On the other hand if drier climate conditions prevail for south-west Western Australia as suggested by Pittock, (1988) due to the Greenhouse Effect, then the lower rainfall would assist in lowering groundwater levels.

7.2 Limitations of Linear Regressions

The regression analyses for groundwater level beneath agroforestry implies that changes in groundwater level are dependent only on annual rainfall, i.e. independent of tree crown cover, rooting depth, depth to groundwater etc. These other variables are time dependent and are not easily quantifiable. Therefore, the regessions should be considered indicative only.

7.3 Plantation Management and Groundwater Level

Trees were culled and final stem densities were established in 1982. After 1982, the rate of decline of minimum groundwater level was fairly uniform. Relative to pasture the reduction was more variable but tended to have a systematic decline over the study period (Fig. 6). This decline is probably attributable to the continuous crown growth of the plantations.

Between 1984 to 1987, the maximum groundwater level under agroforestry remained stable relative to the control site. Most of the time the changes, both under pasture and agroforestry, were closely matched (Fig. 9). This may be due to sensitivity of of maximum groundwater level to rainfall events and time of sampling.

7.4 Effect of Topography and Tree Density on Groundwater Level Reduction

Bores 61218082 and 61218086 are located on the upper slope of the agroforestry plantation where the initial elevation of the water table was higher than the other bores (Fig. 13). The water table decline in these upper slope bores was more rapid than in the lower slope bores (Fig. 12). This would be expected in a system where the transfer of water downslope is faster than the discharge (uptake) of water at the valley floor. At the end of the study period, the slope of the water table was 2% lower than at the begining. Despite the different stem densities, the response of minimum groundwater level in the lower slope bores were similar (Fig. 12). This suggests that the valley, at least, was behaving as one system and the 'local' effects of varying stem density were not observable.

7.5 Groundwater Salinity

The groundwater salinity of pasture bore 61218045 was highly variable; over a few months the variation was more than six-fold (Appendix A). Experience from other experimental sites with similar crown cover and rainfall, suggests that the salinity data are unreliable (Bari et al., 1990). The apparent variation of salinity is probably caused by fresh water leakage from the unsaturated zone at the time of intensive rainfall and/or improper sampling. So, the salinity analysis was limited to the data from the pumped samples collected on 16/5/89 and 6/5/82. The result shows a 44% reduction under pasture over seven years. If the present rate continues, the salinity would be below 1000 mg L^{-1} TSS in a relatively short period of time (1993). Most analyses of solute leaching from a soil indicate an exponential decay of salt with time (e.g. Mulqueen and Kirkham, 1972). However, Peck (1973) notes a near-linear decay in solute concentration in experiments on the displacement of a saline groundwater with increased but uniformly distributed recharge in an inclined soil slab. If this is the case at the control site on Stene's Farm, then serious attention should be given to further analysis of the rate of solute export and groundwater and stream salinity decline in agricultural systems which are in hydrological equilibrium.

The agroforestry bores also experienced fresh water leakage during periods of high rainfall (Appendix A). So, the salinity analysis was limited to comparing the data collected after pumping on 30/5/89 with data from the pumped samples taken on 7/5/82. The result shows a decrease of 6% over the study period. The main significance of this result is that salinities have not increased as a result of evaporative concentration as was assumed likely by a number of authors (e.g. Conacher, 1982; Morris and Thomson, 1983; Williamson, 1986). The slight decrease in groundwater salinity implies that solute leaching from the aquifer beneath the reforestation stand is occurring at a slightly faster rate than increasing concentration due to evapotranspiration of the groundwater. In the situation of a declining groundwater table other processes will also affect groundwater salinity, such as solution-dissolution rates and solute deposition in the unsaturated zone. Compared with the pasture control site it appears agroforestry has limited impact on reducing groundwater salinity. However, this may be masked by the control site bores being located on the mid slopes, whereas the agroforestry bores are on the lower slopes in the valley floor. The leaching in the mid slope area is likely to be greater than in the valley floor, thus exaggerating the difference in salinity reduction.

7.6 Comparison with other Agroforestry Studies

The effects of agroforestry on saline groundwater systems have been reported at two other sites in Western Australia : Flynn's Farm (Bari et al., 1990) and Boundain (Engel, 1987).

The Flynn's Farm agroforestry site is located in Mundaring Weir catchment on essentially the same rainfall isohyet (720 mm) to Stene's agroforestry site. The physiography of the two sites are similar although depth to bedrock is shallower (average 8.3 m) at the Flynn's site. Prior to the establishment of agroforestry 51% of the Flynn's site was cleared for pasture grazing compared to 25% at Stene's agroforestry. The plantations at Flynn's site were located on the lower and midslopes but not in the valley floor as with Stene's site. This may account for the greater average depth to the water table beneath the plantations at Flynn's site (4.4 m) compared to Stene's site (2.7 m). Similarly, the location of plantation could account for the lower mean salinity at Flynn's site (2400 mg L^{-1}) compared to the Stene's site (6600 mg L^{-1}). The principal species planted at Flynn's were P. pinaster (12%), P. radiata (81%) and E. camaldulensis (7%) whereas at Stene's the principal species were E. camaldulensis (59%), E. calophylla (1%), E. sargentii (30%) and E. wandoo (10%).

At Flynn's, 58% of the farmland was planted at an initial density of 380-1140 sph while at Stene's the initial planting density was 1250 sph. These plantings were later thinned to 75 - 225 sph at Flynn's and 150-900 sph at Stene's. The average crown cover in the agroforestry plantations were 14% (Flynn's) and 25% (Stene's).

The greater reduction in minimum groundwater level relative to a control at Stene's site (2.0 m) than Flynn's site (1.1 m) was probably due to the higher tree cover at Stene's, the annual pruning of the pines at Flynn's site until 1988, and the lower rainfall at Stene's site in the latter three years (1772 mm compared to 1958 mm at Flynn's site). The response of the minimum water table at Stene's agroforestry was strongly biased by the two piezometers at the highest elevation in the agroforestry plantation.

The groundwater salinity at both Flynn's and Stene's agroforestry sites decreased slightly (9% and 6% respectively). The Stene's salinity data, however, were less reliable. Nevertheless a decrease in groundwater salinity was unexpected and indicates that the concentration of salts due to evapotranspiration is not a dominating process in these locations.

The second site, Boundain, is located 25 km east of Narrogin in the Yilliminning River catchment and has an annual rainfall slightly less than 500 mm. The site is typical of the extensively cleared wheatbelt where saline seeps are expanding. Compared to Stene's agroforestry, the site conditions for planting were more severe (mean depth to water table 1.3 m, salinity 2000-17000 mg L^{-1}). Species were planted based on their salt tolerance, ranging from E. globulus on non-saline areas to Casuarina glauca on salt affected land. More than 95% of the site was cleared but only 21% planted at stem densities of 83 and 166 sph. Despite this there was a mean depression in groundwater level across the site of 0.9 m and a maximum depression (beneath the 166 sph stand) of 1.9 m. These substantial reductions relative to Stene's agroforestry are probably due to the significantly lower rainfall at Boundain. Groundwater salinities at Boundain were found to increase on average which may be due to the lower rainfall and poorer drainage characteristics compared to Stene's agroforestry site.

7.7 Use of Agroforestry as Salinity Control

The results demonstrate that agroforestry is successful in lowering the saline groundwater table across the valley floor, which should reduce saline groundwater discharge to the stream in a relatively short period (~10 years) of time. In general, the effectiveness of the agroforestry can be increased by increasing the proportion of the farmland planted, retaining higher stem density, and using faster growing and/or higher transpiring trees. The design of an agroforestry layout should take into account the water balance of the site, particularly the annual rainfall (Schofield, 1990b). This would have direct relevance to an on-going large scale reforestation programme based on this strategy in the Collie catchment (Loh, 1988).

8. CONCLUSIONS

Based on the analyses and interpretation of data, the following conclusions can be drawn:

8.1 Groundwater Level

(i) Agroforestry covering 57% of the farmland at a final stem density of 150-625 sph has lowered the minimum groundwater level by 1.7 m. The reduction relative to the pasture control was 2.0 m. The annual minimum had a continuous downward trend.

(ii) Agroforestry also reduced the maximum groundwater level by 0.65 m and by 1.1 m relative to the pasture.

(iii) During the study period, rainfall was 13% lower than the long term average. Under long term rainfall conditions, the rate of decline of minimum groundwater table beneath agroforestry could have been significantly less.

8.2 Groundwater Flow

(i) Groundwater flow was towards the stream.

(ii) Although reforestation reduced groundwater levels it did not alter the direction of flow.

8.3 Groundwater Salinity

(i) The spatial variation of groundwater salinity at both the agroforestry and control sites was high (fresh to highly saline).

(ii) During the study period the groundwater salinity under agroforestry decreased by about 5%. This decrease was contrary to early expectations.

(iii) The groundwater salinity beneath pasture decreased by about 40% over the study period. This result merits further investigation of solute leaching under agriculture in moderate to high rainfall zones.

(iv) The effectiveness of the agroforestry site in reducing groundwater salinity appears to be limited, but further monitoring is required to determine longer term effects.

9. RECOMMENDATIONS

- Agroforestry appears to be a viable landuse option for reducing saline discharge to streams and its further study is strongly recommended.

- To identify the effects of further crown and tree growth, bore monitoring should be continued and the yearly minimum and maximum groundwater levels should be identified.

- Bore salinity sampling should be continued to determine ongoing groundwater salinity behaviour under both pasture and agroforestry. This monitoring programme is detailed in the Research Operation and Data Review for South West Region.

- To support interpretation of the groundwater data, tree basal area and tree covers should be measured in approximately 5 year intervals.

10. ACKNOWLEDGEMENTS

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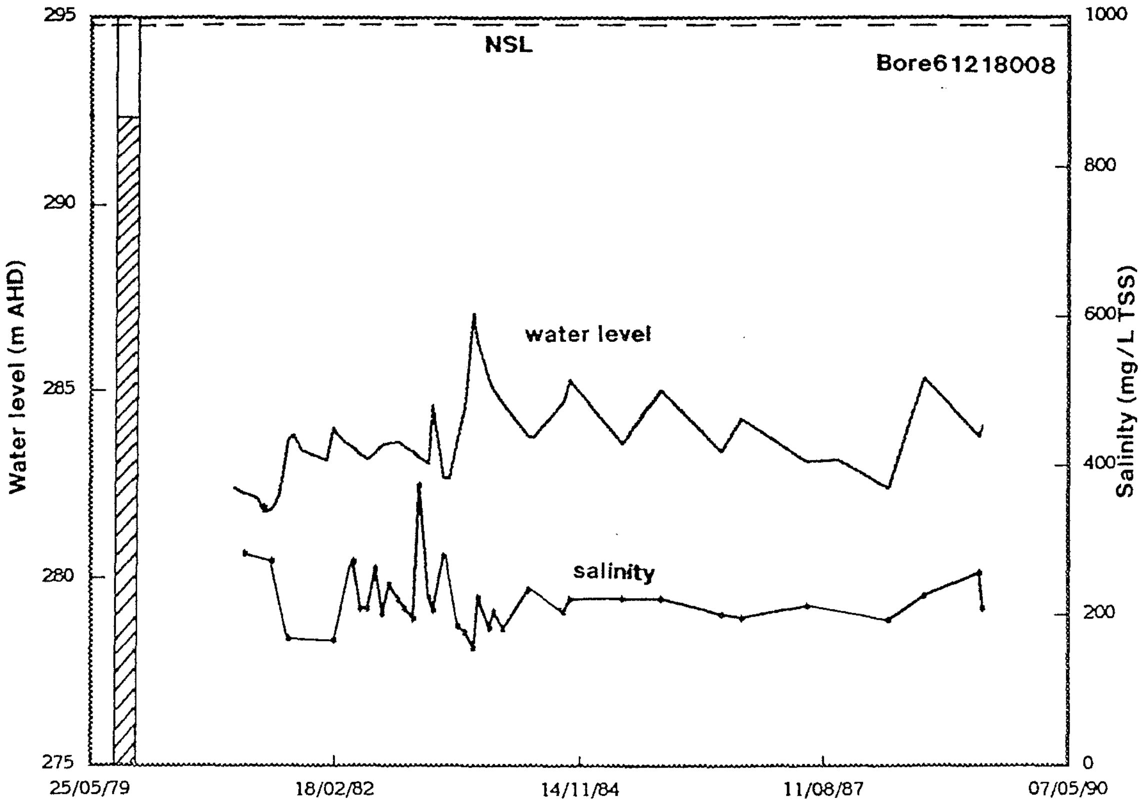
APPENDIX A

Groundwater Level and Salinity
Time Series for each Agroforestry
and control bore

mbar2



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290
285
280
275
Water level (m AHD)
NSL
Bore61218008
water level
salinity
1000
800
600
400
200
0
Salinity (mg/L TSS)
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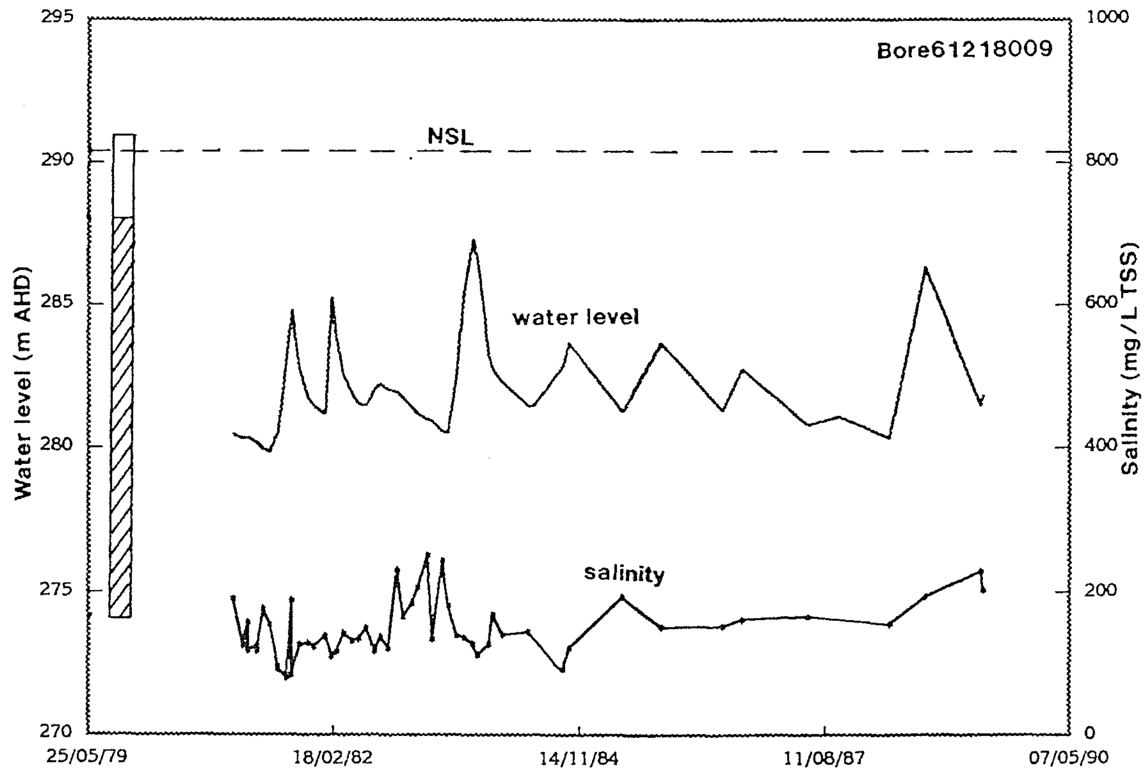
18/02/82
14/11/84
11/08/87
07/05/90



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285
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Water level (m AHD)
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NSL
water level
salinity
1000
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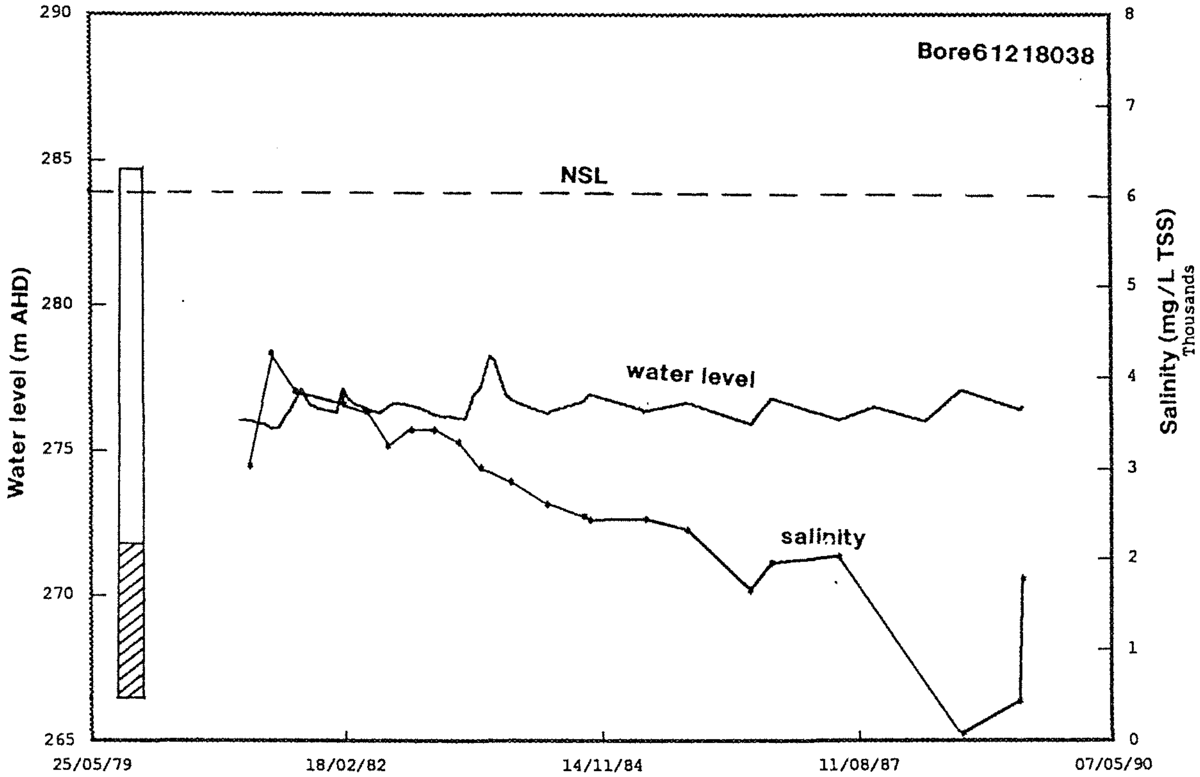
200
0
Salinity (mg/L TSS)
25/05/79
18/02/82
14/11/84
11/08/87
07/05/90


Bore61218038
NSL
water level
salinity
Water level (m AHD)
Salinity (mg/L TSS) Thousands
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280
275
270
265
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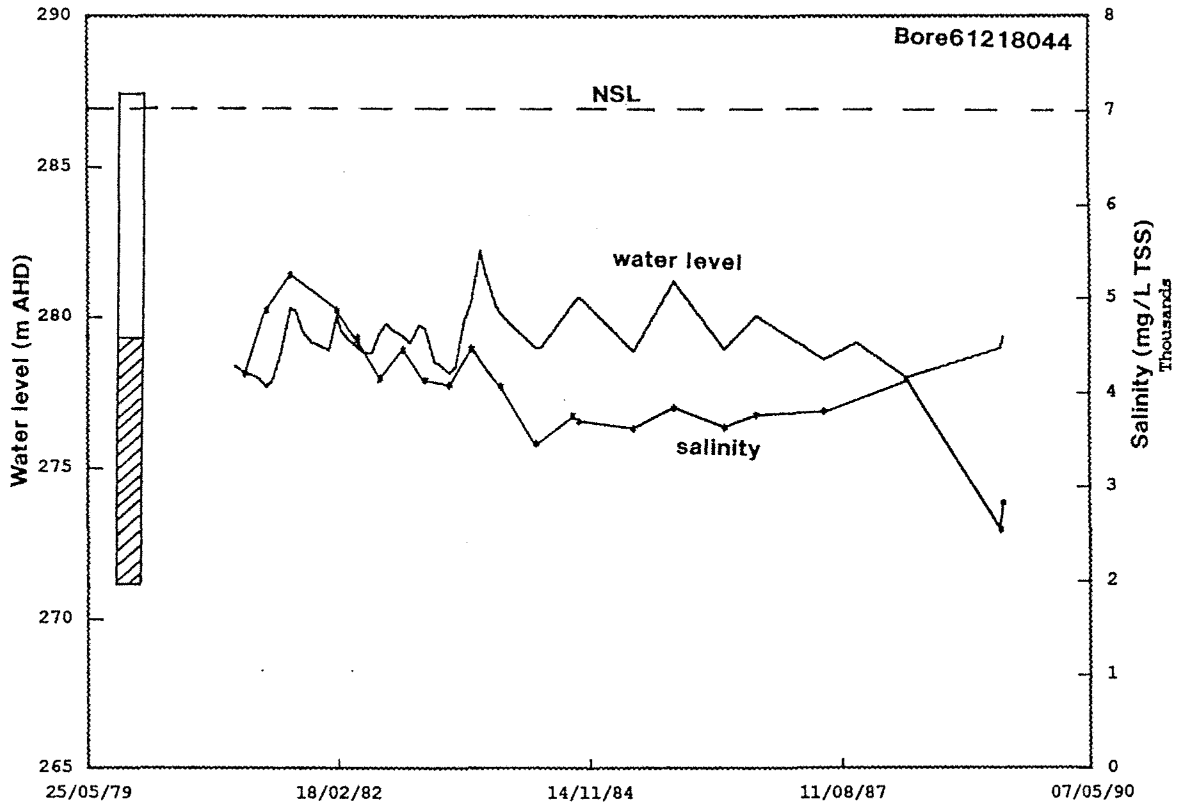
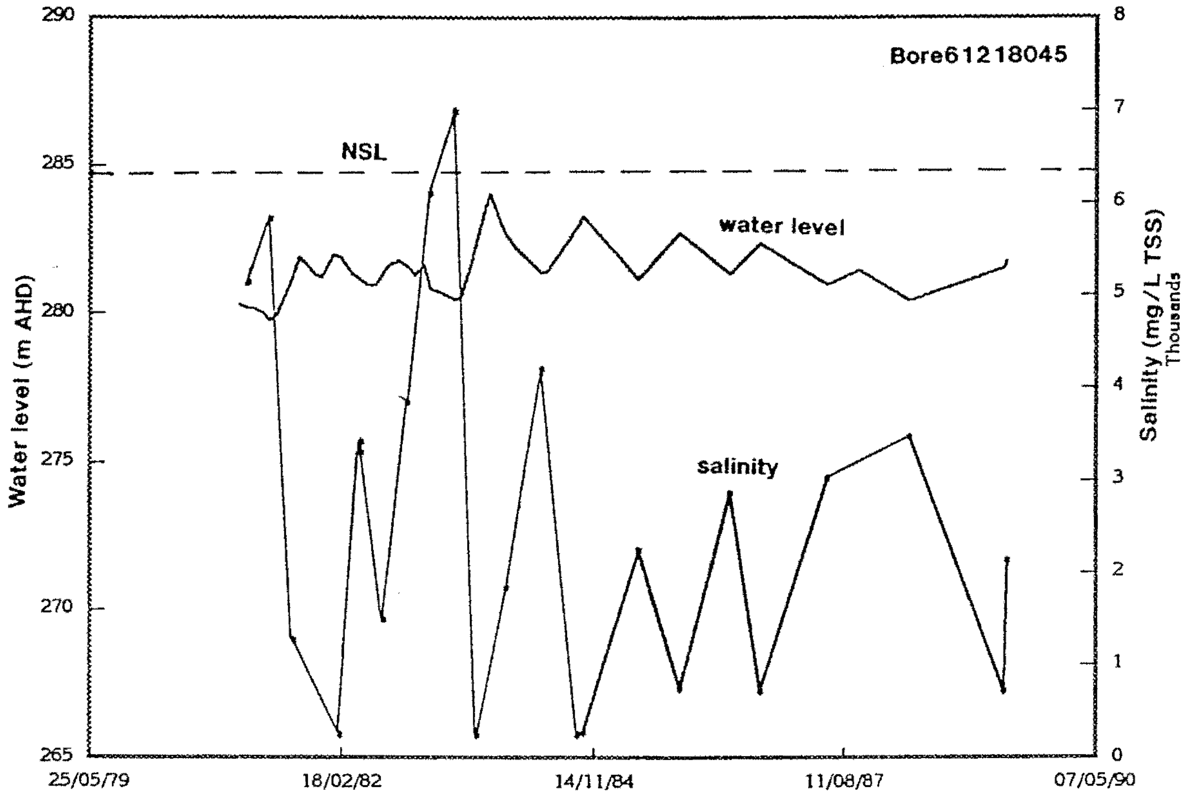
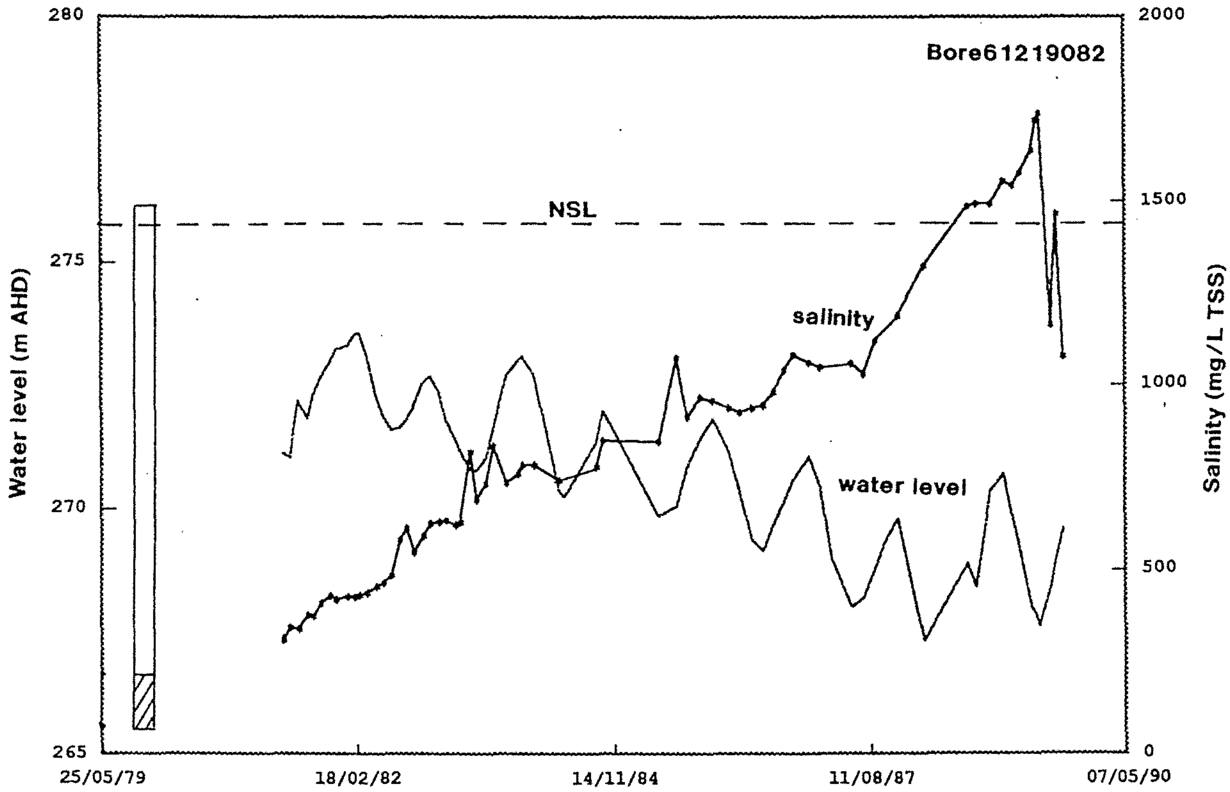
7
6
5
4
3
2
1
0
25/05/79
18/02/82
14/11/84
11/08/87
07/05/90

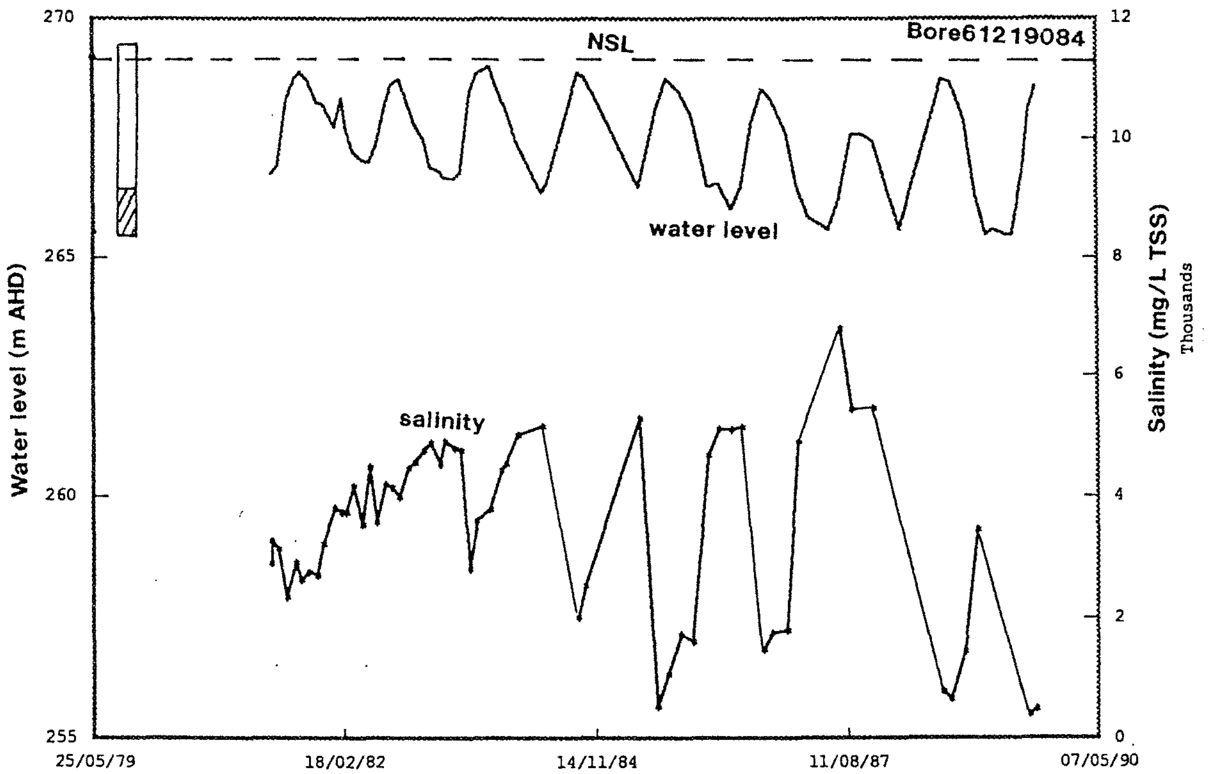

Bore61218044
NSL
water level
salinity
Water level (m AHD)
Salinity (mg/L TSS) Thousands
290
285
280
275
270
265
8
7
6
5
4
3
2
1
0
25/05/79
18/02/82
14/11/84
11/08/87
07/05/90



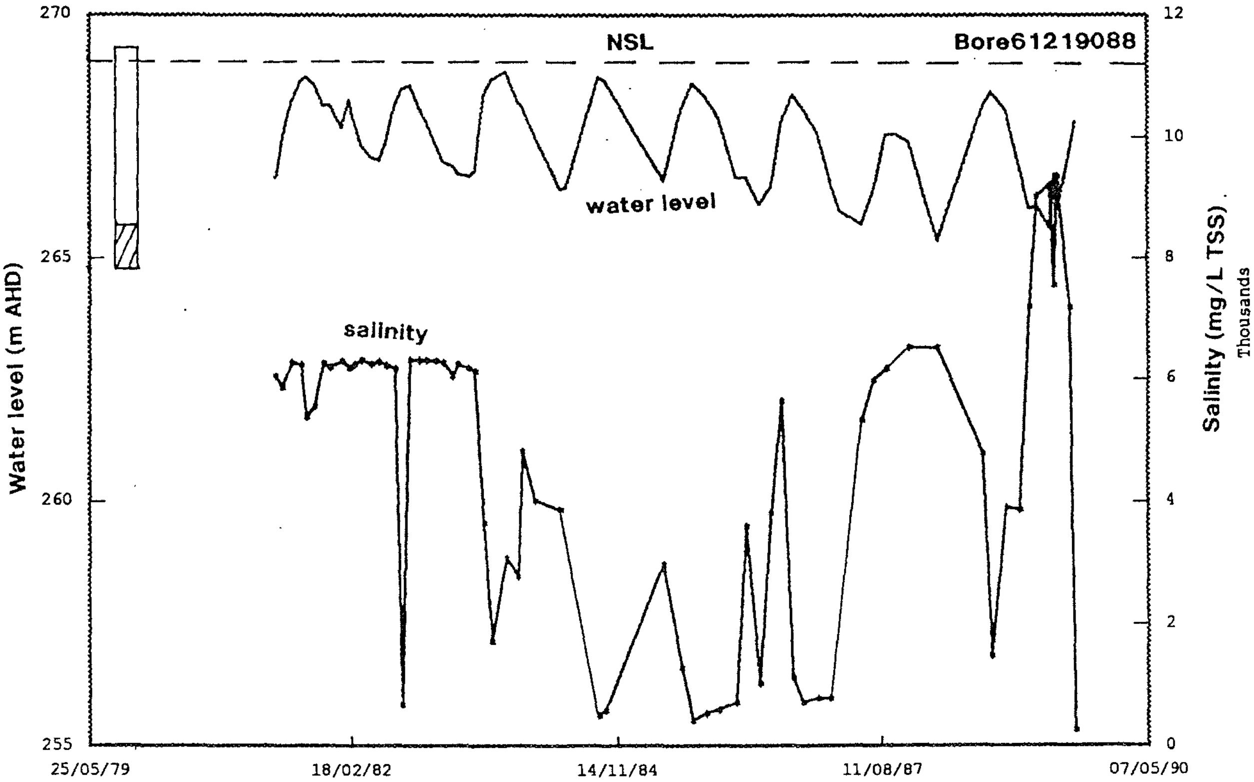
Bore61218045
NSL
water level
salinity
Water level (m AHD)
Salinity (mg/L TSS) Thousands
290
285
280
275
270
265
8
7
6
5
4
3
2
1
0
25/05/79
18/02/82
14/11/84
11/08/87
07/05/90



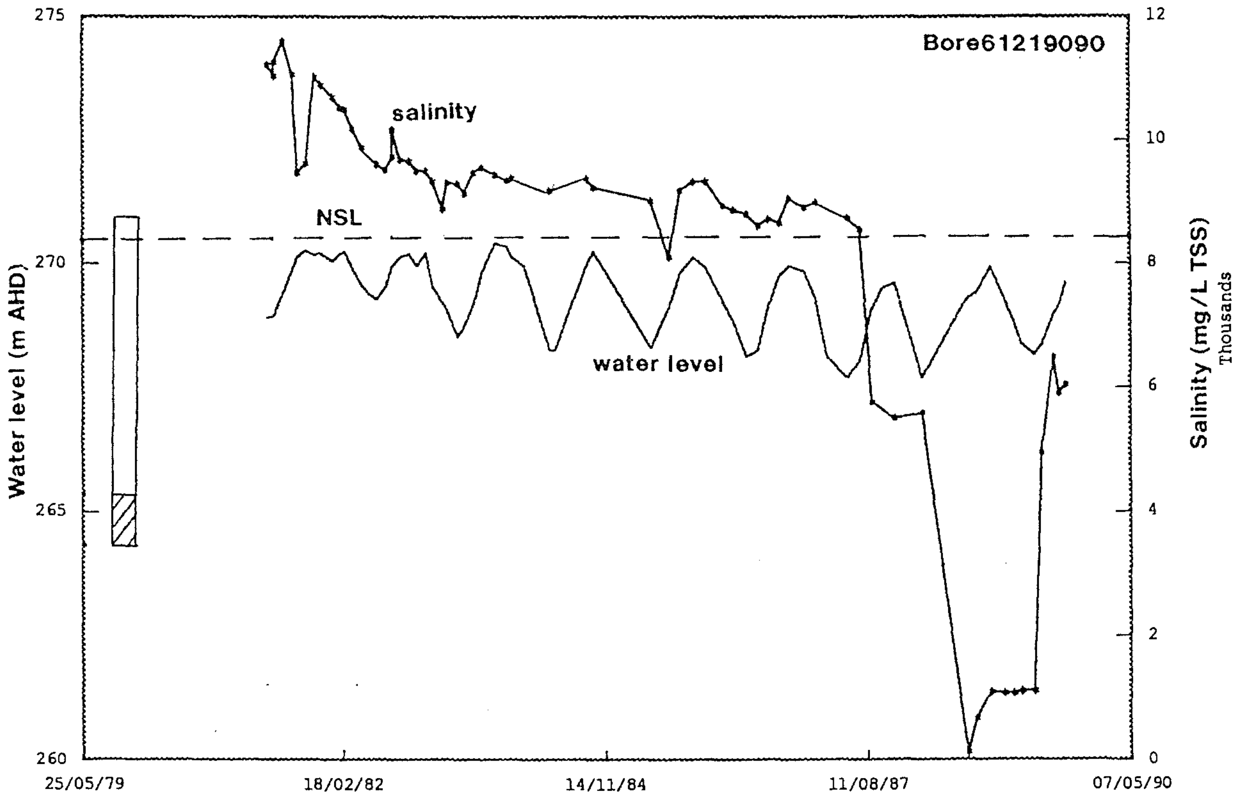
Bore61219082
NSL
salinity
water level
Water level (m AHD)
Salinity (mg/L TSS)
280
275
270
265
2000
1500
1000
500
0
25/05/79
18/02/82
14/11/84
11/08/87
07/05/90



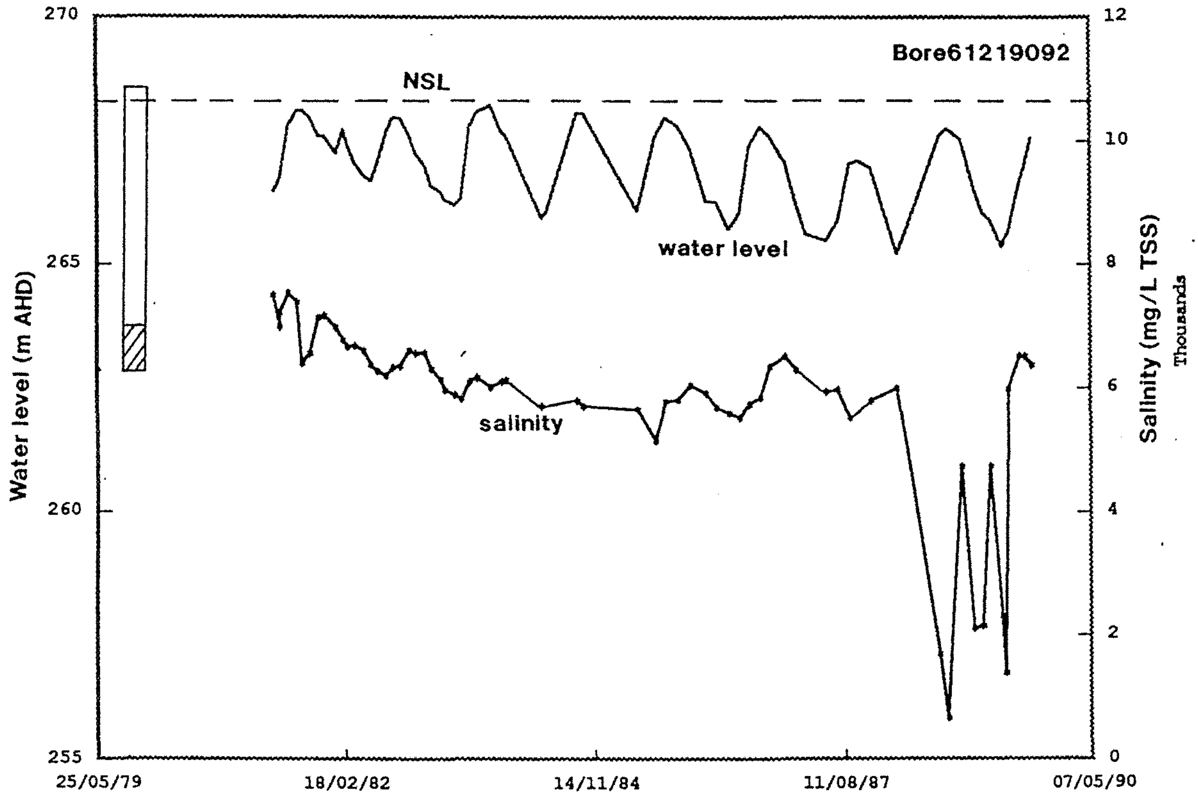
Bore61219084
NSL
water level
salinity
Water level (m AHD)
Salinity (mg/L TSS)
Thousands
270
265
260
255
12
10
8
6
4
2
0
25/05/79
18/02/82
14/11/84
11/08/87
07/05/90



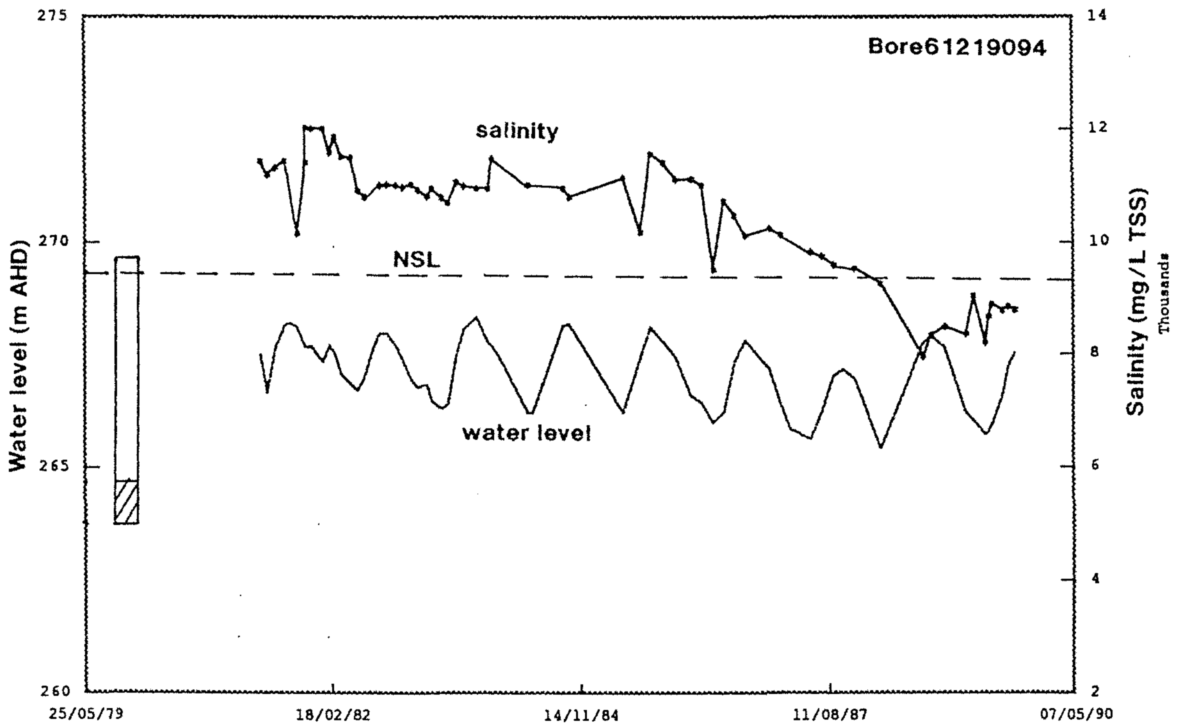
270
265
260
255
12
10
8
6
4
2
0
NSL
Bore61219088
water level
salinity
Water level (m AHD)
Salinity (mg/L TSS)
Thousands
25/05/79
18/02/82
14/11/84
11/08/87
07/05/90



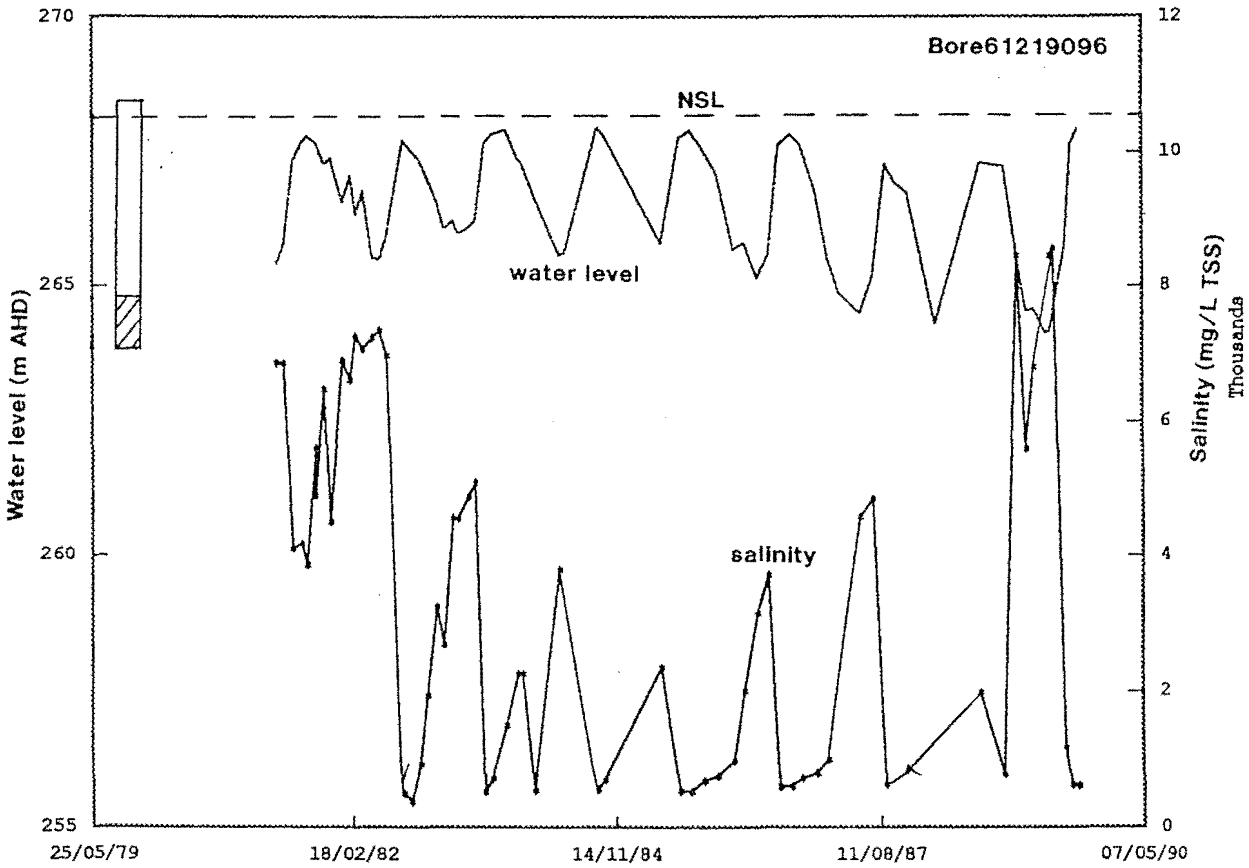
275
270
265
260
12
10
8
6
4
2
0
Bore61219090
salinity
NSL
water level
Water level (m AHD)
Salinity (mg/L TSS)
Thousands
25/05/79
18/02/82
14/11/84
11/08/87
07/05/90



Bore61219092
NSL
water level
salinity
Water level (m AHD)
Salinity (mg/L TSS)
Thousands
270
265
260
255
12
10
8
6
4
2
0
25/05/79
18/02/82
14/11/84
11/08/87
07/05/90



Bore61219094
salinity
NSL
water level
Water level (m AHD)
Salinity (mg/L TSS)
Thousands
275
270
265
260
14
12
10
8
6
4
2
25/05/79
18/02/82
14/11/84
11/08/87
07/05/90


Bore61219096
NSL
water level
salinity
Water level (m AHD)
Salinity (mg/L TSS)
Thousands
270
265
260
255
12
10
8
6
4
2
0
25/05/79
18/02/82
14/11/84
11/08/87
07/05/90